BRITISH STANDARD

BS EN 61788-1:2007

Superconductivity —

Part 1: Critical current measurement — DC critical current of Nb-Ti composite superconductors

The European Standard EN 61788-1:2007 has the status of a British Standard

ICS 17.220; 29.050

British Standards

National foreword

This British Standard was published by BSI. It is the UK implementation of EN 61788-1:2007. It is identical with IEC 61788-1:2006. It supersedes BS EN 61788-1:1998 which is withdrawn.

The UK participation in its preparation was entrusted to Technical Committee L/-/90, Superconductivity.

A list of organizations represented on L/-/90 can be obtained on request to its secretary.

This publication does not purport to include all the necessary provisions of a contract. Users are responsible for its correct application.

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Superconductivity
Part 1: Critical current measurement - DC critical current of Nb-Ti composite superconductors
(IEC 61788-1:2006)

Supraconductivité
Partie 1: Mesure du courant critique - Courant critique continu de supraconducteurs en composite Nb-Ti
(CEI 61788-1:2006)

Supraleitfähigkeit
Teil 1: Messen des kritischen Stromes - Kritischer Strom (Gleichstrom) von Nb-Ti Verbundsupraleitern
(IEC 61788-1:2006)

This European Standard was approved by CENELEC on 2006-12-01. CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration.

Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the Central Secretariat or to any CENELEC member.

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CENELEC

European Committee for Electrotechnical Standardization
Comité Européen de Normalisation Electrotechnique
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Foreword

The text of document 90/196/FDIS, future edition 2 of IEC 61788-1, prepared by IEC TC 90, Superconductivity, was submitted to the IEC-CENELEC parallel vote and was approved by CENELEC as EN 61788-1 on 2006-12-01.

This European Standard supersedes EN 61788-1:1998.

It includes the following significant technical changes with respect to EN 61788-1:1998:

– the addition of normative Annex C and informative Annex D;

– accuracy and precision statements were converted to uncertainty statements;

– the magnetic field uniformity statement was tightened from ± 2 % to be less than the larger of 0,5 % or 0,02 T.

The following dates were fixed:

– latest date by which the EN has to be implemented at national level by publication of an identical national standard or by endorsement	(dop)	2007-09-01
– latest date by which the national standards conflicting with the EN have to be withdrawn	(dow)	2009-12-01

Annex ZA has been added by CENELEC.

Endorsement notice

The text of the International Standard IEC 61788-1:2006 was approved by CENELEC as a European Standard without any modification.

CONTENTS

INTRODUCTION

The critical currents of composite superconductors are used to establish design limits for applications of superconducting wires. The operating conditions of superconductors in these applications determine much of their behaviour, and tests made with the method given in this part of IEC 61788 may be used to provide part of the information needed to determine the suitability of a specific superconductor.

Results obtained from this method may also be used for detecting changes in the superconducting properties of a composite superconductor due to processing variables, handling, ageing or other applications or environmental conditions. This method is useful for quality control, acceptance or research testing, if the precautions given in this standard are observed.

The critical current of composite superconductors depends on many variables. These variables need to be considered in both the testing and the application of these materials. Test conditions such as magnetic field, temperature and relative orientation of the specimen, current and magnetic field are determined by the particular application. The test configuration may be determined by the particular conductor through certain tolerances. The specific critical current criterion may be determined by the particular application. It may be appropriate to measure a number of test specimens if there are irregularities in testing.

SUPERCONDUCTIVITY –

Part 1: Critical current measurement – DC critical current of Nb-Ti composite superconductors

1 Scope

This part of IEC 61788 covers a test method for the determination of the d.c. critical current of either Cu/Nb-Ti composite superconductors that have a copper/superconductor ratio larger than 1 or Cu/Cu-Ni/Nb-Ti wires that have a copper/superconductor ratio larger than 0,9 and a copper alloy (Cu-Ni)/superconductor ratio larger than 0,2, where the diameter of Nb-Ti superconducting filaments is larger than 1 μm. The changes for the Cu/Cu-Ni/Nb-Ti are described in Annex C. The Cu-Ni uses all of the main part of the standard with the exceptions listed in Annex C that replace (and in some cases are counter to) some of the steps in the main text.

This method is intended for use with superconductors that have critical currents less than 1 000 A and *n*-values larger than 12, under standard test conditions and at magnetic fields less than or equal to 0,7 of the upper critical magnetic field. The test specimen is immersed in a liquid helium bath at a known temperature during testing. The test conductor has a monolithic structure with a round or rectangular cross-sectional area that is less than 2 mm^2. The specimen geometry used in this test method is an inductively coiled specimen. Deviations from this test method that are allowed for routine tests and other specific restrictions are given in this standard.

Test conductors with critical currents above 1 000 A or cross-sectional areas greater than 2 mm^2 could be measured with the present method with an anticipated increase in uncertainty and a more significant self-field effect (see Annex B). Other, more specialized, specimen test geometries may be more appropriate for larger conductor testing which have been omitted from this present standard for simplicity and to retain a lower uncertainty.

The test method given in this standard is expected to apply to other superconducting composite wires after some appropriate modifications.

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 standard, the terms and definitions given in IEC 60050-815, some of which are repeated here for convenience, and the following apply.

3.1
critical current
I_c
maximum direct current that can be regarded as flowing without resistance

NOTE I_c is a function of magnetic field strength and temperature.

[IEV 815-03-01]

3.2
critical current criterion
***I_c* criterion**
criterion to determine the critical current, I_c, based on the electric field strength, E, or the resistivity, ρ

NOTE E = 10 µV/m or E = 100 µV/m is often used as the electric field strength criterion, and $\rho = 10^{-13}$ Ω·m or $\rho = 10^{-14}$ Ω·m is often used as the resistivity criterion.

[IEV 815-03-02, modified]

3.3
***n*-value** (of a superconductor)
exponent obtained in a specific range of electric field strength or resistivity when the voltage/current $U(I)$ curve is approximated by the equation $U \propto I^n$

[IEV 815-03-10]

3.4
quench
uncontrollable and irreversible transition of a superconductor or a superconducting device from the superconducting state to the normal conducting state

NOTE A term usually applied to superconducting magnets.

[IEV 815-03-11]

3.5
three-component superconducting wire
composite superconducting wire composed of a superconducting component and two normal conducting materials

NOTE This term is mostly used for Cu/Cu-Ni/Nb-Ti composite superconductors

[IEV 815-04-33]

3.6
Lorentz force (on fluxons)
force applied to fluxons by a current

NOTE 1 The force per unit volume is given by $J \times B$, where J is a current density, and B is a magnetic flux density.

NOTE 2 "Lorentz force" is defined in IEV 121-11-20.[1][1)].

[IEV 815-03-16]

3.7
current transfer (of composite superconductor)
phenomenon that a d.c. current transfers spatially from filament to filament in a composite superconductor, resulting in a voltage generation along the conductor

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1) Figures in square brackets refer to the Bibliography.

NOTE In the I_c measurement, this phenomenon appears typically near the current contacts where the injected current flows along the conductor from periphery to inside until uniform distribution among filaments is accomplished.

3.8

constant sweep rate method

a *U-I* data acquisition method where a current is swept at a constant rate from zero to a current above I_c while frequently and periodically acquiring *U-I* data

3.9

ramp-and-hold method

a *U-I* data acquisition method where a current is ramped to a number of appropriately distributed points along the *U-I* curve and held constant at each one of these points while acquiring a number of voltages and current readings

4 Principle

The critical current of a composite superconductor is determined from a voltage (U) – current (I) characteristic measured at a certain value of a static applied magnetic field strength (magnetic field) at a specified temperature in a liquid cryogen bath at a constant pressure. To get a *U-I* characteristic, a direct current is applied to the superconductor specimen and the voltage generated along a section of the specimen is measured. The current is increased from zero and the *U-I* characteristic generated is recorded. The critical current is determined as the current at which a specific electric field strength (electric field) criterion (E_c) or resistivity criterion (ρ_c) is reached. For either E_c or ρ_c, there is a corresponding voltage criterion (U_c) for a specified voltage tap separation.

5 Requirements

The critical current of a superconductor shall be measured by applying a direct current (I) to the superconductor specimen and then measuring the voltage (U) generated along a section of the specimen. The current shall be increased from zero and the voltage-current (*U-I*) characteristic generated and recorded.

The specimen shall be affixed to the measurement mandrel with sufficient tension or a low temperature adhesive.

NOTE 1 Exception C.2.1 replaces this sentence for Cu/Cu-Ni/Nb-Ti specimens.

The target uncertainty of this method is defined as a coefficient of variation (standard deviation divided by the average of the critical current determinations) that shall not exceed 3 % in an interlaboratory comparison.

NOTE 2 Exception C.2.2 replaces this sentence for Cu/Cu-Ni/Nb-Ti specimens.

The use of a common current transfer correction is excluded from this test method. Furthermore, if a current transfer signature is pronounced in the measurement, then the measurement shall be considered invalid.

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. Specific precautionary statements are given below.

Hazards exist in this type of measurement. Very large direct currents with very low voltages do not necessarily provide a direct personal hazard, but accidental shorting of the leads with another conductor, such as tools or transfer lines, can release significant amounts of energy and cause arcs or burns. It is imperative to isolate and protect current leads from shorting. Also the stored energy in superconducting magnets commonly used for the background magnetic field can cause similar large current and/or voltage pulses or deposit large amounts of thermal energy in the cryogenic systems causing rapid boil-off or even explosive conditions. Under rapid boil-off conditions, cryogens can create oxygen-deficient conditions in the immediate area and additional ventilation may be necessary. The use of cryogenic liquids is essential to cool the superconductors to allow transition into the superconducting state. Direct contact of skin with cold liquid transfer lines, storage dewars or apparatus components can cause immediate freezing, as can direct contact with a spilled cryogen. If improperly used, liquid helium storage dewars can freeze air or water in pressure vent lines and cause the dewar to over-pressurize and fail despite the common safety devices. The use of liquid hydrogen is not recommended and not necessary for these measurements. It is imperative that safety precautions for handling cryogenic liquids be observed.

6 Apparatus

6.1 Measurement mandrel material

The measurement mandrel shall be made from an insulating material or from a conductive non-ferromagnetic material that is either covered or not covered with an insulating layer.

The tensile strain at the measuring temperature, induced by the differential thermal contraction of the specimen and the measurement mandrel, shall not exceed 0,2 %.

Suitable mandrel materials are recommended in Annex A. Any one of these may be used.

NOTE 1 Exception C.2.3 replaces this sentence for Cu/Cu-Ni/Nb-Ti specimens.

When a conductive material is used without an insulating layer, the leakage current through the mandrel shall be less than 0,2 % of the total current when the specimen current is at I_c (see 9.5 and A.3.1).

NOTE 2 Exception C.2.4 replaces this sentence for Cu/Cu-Ni/Nb-Ti specimens.

6.2 Mandrel construction

The diameter of the mandrel shall be larger than 24 mm and consistent with the bending strain limit (see 7.2).

Preferably the mandrel shall have a helical groove in which the specimen shall be wound. The pitch angle of the groove shall be less than 7°.

If no helical groove is used to wind the specimen, the same conditions given for the pitch angle shall be met. This approach to winding the specimen could result in inadequate support of the specimen and larger variation in the pitch angle of the specimen (see 7.2).

The angle between the specimen axis (portion between the voltage taps) and the magnetic field shall be (90 ± 7)°. This angle shall be determined with a combined standard uncertainty not to exceed 1°.

The current contact shall be rigidly fastened to the measurement mandrel to avoid stress concentration on the specimen in the region of transition between the mandrel and the current contact.

7 Specimen preparation

7.1 Specimen bonding

Winding tension and/or a low temperature adhesive (such as silicone vacuum grease, Apiezon® [2)] vacuum grease or epoxy) shall be used to bond the specimen to the measurement mandrel to reduce specimen motion. When a low-temperature adhesive is used, a minimum shall be applied and the excess adhesive shall be removed from the outer surface of the specimen after the specimen has been mounted.

NOTE 1 Exception C.2.5 replaces this sentence for Cu/Cu-Ni/Nb-Ti specimens.

The adequacy of specimen bonding shall be demonstrated by a successful completion of the specified critical current repeatability.

Solder shall not be used to bond the specimen to the mandrel between the current contacts.

NOTE 2 Exception C.2.6 replaces this sentence for Cu/Cu-Ni/Nb-Ti specimens.

7.2 Specimen mounting

There shall be no joints or splices in the test specimen.

The cross-sectional area *S* of the specimen shall be determined in the plane transverse to the axis of the conductor with a combined standard uncertainty not to exceed 2,5 %.

The wire shall be wound in the shape of a small coil in an inductive manner. The specimen shall not be wound in a manner that would introduce additional twists into the specimen.

For a wire with a rectangular cross-section, the specimen shall be wound in a coil so that the applied magnetic field is parallel to the wide face of the specimen.

To ensure that the specimen is well-seated in the groove, a tensile force shall be applied to the wire during winding and this force shall not result in more than 0,1 % tensile strain (see Annex D) on the wire.

NOTE Exception C.2.7 replaces this sentence for Cu/Cu-Ni/Nb-Ti specimens.

The maximum bending strain induced during the mounting of the specimen shall not exceed 3 %.

Both ends of the wire shall be fixed to the current contact with solder. The minimum length of the soldered part of the current contact shall be the largest of 40 mm, 30 wire diameters or 30 wire thicknesses.

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2) Apiezon® is the trade name of a product supplied by M&I Materials Ltd., UK (www.apiezon.com).This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the product named. Equivalent products may be used if they can be shown to lead to the same results.

No more than three turns of the specimen shall be soldered onto each current contact.

The shortest distance from a current contact to a voltage tap shall be greater than 40 mm.

The voltage taps shall be soldered to the specimen. Minimize the mutual inductance between the specimen current and the area formed by the specimen and the voltage taps by counterwinding the untwisted section of the voltage taps back along the specimen, as shown in Figure A.1.

The distance L along the specimen between the voltage taps shall be measured with a combined standard uncertainty not to exceed 2,5 %. This voltage tap separation shall be greater than 50 mm.

For testing, the specimen and mandrel shall be mounted in a test cryostat consisting of a liquid helium dewar, a magnet and support structure, and a specimen support structure.

8 Measurement procedure

The specimen shall be immersed in liquid helium for the data acquisition phase. The temperature of the liquid helium bath shall be measured before and after each determination of I_c.

The specimen current shall be kept low enough so that the specimen does not enter the normal state unless a quench protection circuit or resistive shunt is used to protect the specimen from damage.

When using the constant sweep rate method, the time for the ramp from zero current to I_c shall be more than 10 s.

When using the ramp-and-hold method, the current sweep rate between current set points shall be lower than the equivalent of ramping from zero current to I_c in 3 s.

The d.c. magnetic field shall be applied in the direction of the mandrel axis. The relation between the magnetic field and the magnet current shall be measured beforehand. The magnet current shall be measured before each determination of I_c. The applied magnetic field shall be parallel to the wide face and orthogonal to the wire axis of the specimens with rectangular cross-sections.

The direction of the current and the applied magnetic field shall result in an inward Lorentz force over the length of the specimen between the voltage taps.

NOTE Exception C.2.8 replaces this sentence for Cu/Cu-Ni/Nb-Ti specimens.

Record the U-I characteristic of the test specimen under test conditions and monotonically increasing current.

A valid U-I characteristic shall give an I_c with a standard deviation obtained under repeatability conditions not to exceed 0,5 % and the characteristic shall be stable with time for voltages at or below the critical current criterion.

The baseline voltage of the *U-I* characteristic shall be taken as the recorded voltage at zero current for the ramp and hold current method, or the average voltage at approximately 0,1 I_c for the constant sweep rate method.

9 Uncertainty of the test method

9.1 Critical current

The critical current shall be determined from a voltage-current characteristic measured with a four-terminal technique.

The current source shall provide a d.c. current having a maximum periodic and random deviation of less than ±2 % at I_c, within the bandwidth 10 Hz to 10 MHz.

A four-terminal standard resistor, with a combined standard uncertainty not to exceed 0,25 %, shall be used to determine the specimen current.

A recorder and necessary preamplifiers, filters or voltmeters, or a combination thereof, shall be used to record the *U-I* characteristic. The resulting record shall allow the determination of U_c with a combined standard uncertainty not to exceed 5 % and the corresponding current with a combined standard uncertainty not to exceed 0,5 %.

9.2 Temperature

A cryostat shall provide the necessary environment for measuring I_c and the specimen shall be measured while immersed in liquid helium. The liquid helium bath shall be operated so that the bath temperature is near the normal boiling point for the typical atmospheric pressure of the test site. The specimen temperature is assumed to be the same as the temperature of the liquid. The liquid temperature shall be reported with a combined standard uncertainty not to exceed 0,01 K, measured by means of a pressure sensor or an appropriate temperature sensor.

The difference between the specimen temperature and the bath temperature shall be minimized.

For converting the observed pressure in the cryostat into a temperature value, the phase diagram of helium shall be used. The pressure measurement shall have an uncertainty that is low enough to obtain the required uncertainty of the temperature measurement. For liquid helium depths greater than 1 m, a head correction may be necessary.

9.3 Magnetic field

A magnet system shall provide the magnetic field with a combined standard uncertainty not to exceed 0,5 % or 0,01 T, whichever is larger.

The magnetic field, over the length of the specimen between the voltage contacts, shall have a uniformity not to exceed 0,5 % or 0,02 T, whichever is larger.

The maximum periodic and random deviation of the magnetic field shall not exceed ±1 % or ±0,02 T, whichever is larger.

9.4 Specimen and mandrel support structure

The support structure shall provide an adequate support for the specimen and the orientation of the specimen with respect to the magnetic field. The specimen support is adequate if it allows additional determinations of critical current with the repeatability described in Clause 8.

The test configuration of the specimen shall be an inductive coil

9.5 Specimen protection

If a resistive shunt or quench protection circuit is used in parallel with the specimen, then the current through the shunt or the circuit shall be less than 0,2 % of the total current at I_c.

10 Calculation of results

10.1 Critical current criteria

The critical current, I_c, shall be determined by using an electric field criterion, E_c, or a resistivity criterion, ρ_c, where the total cross-section of the composite superconductor is preferred for the estimation of the resistivity (see Figures 1 and 2).

In the case of an electric field criterion, two values of I_c shall be determined at criteria of 10 μV/m and 100 μV/m. In the other case, two values of I_c shall be determined at resistivity criteria of 10^{-14} Ωm and 10^{-13} Ωm.

When it is difficult to measure the I_c properly at a criterion of 100 μV/m, an E_c criterion less than 100 μV/m must be substituted. Otherwise, the measurements using the resistivity criterion are recommended.

The I_c shall be determined as the current corresponding to the point on the *U-I* curve where the voltage is U_c measured relative to the baseline voltage (see Figures 1 and 2):

$$U_c = L\,E_c \qquad (1)$$

where

U_c is the voltage criterion, in microvolts;

L is the voltage tap separation, in metres;

E_c is the electric field criterion, in microvolts/metre.

or, when using a resistivity criterion:

$$U_c = I_c\,\rho_c\,L/S \qquad (2)$$

where

U_c, I_c and ρ_c are the corresponding voltage, current and resistivity to the intersecting point of a straight line with the *U-I* curve as shown in Figure 1, and

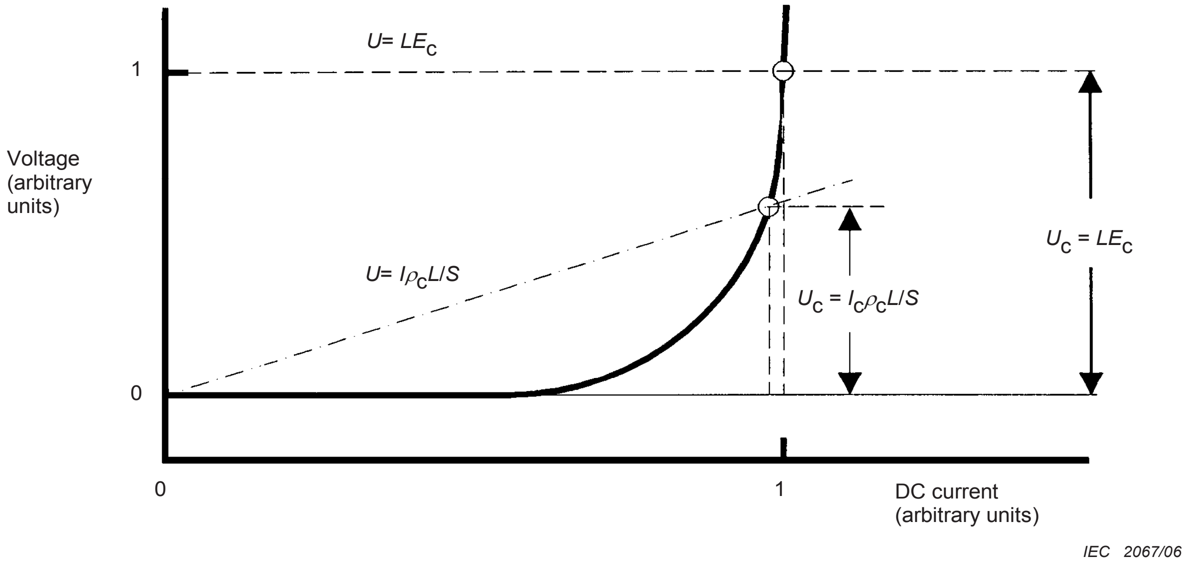
S is the overall cross-sectional area in square metres.

A straight line shall be drawn from the baseline voltage to the average voltage near 0,7 I_c (see Figures 1 and 2). A finite slope of this line may be due to current transfer. A valid determination of I_c requires that the slope of the line be less than 0,3 U_c/I_c, where U_c and I_c are determined at a criterion of 10 μV/m or 10^{-14} Ωm.

10.2 *n*-value (optional calculation, refer to A.7.2)

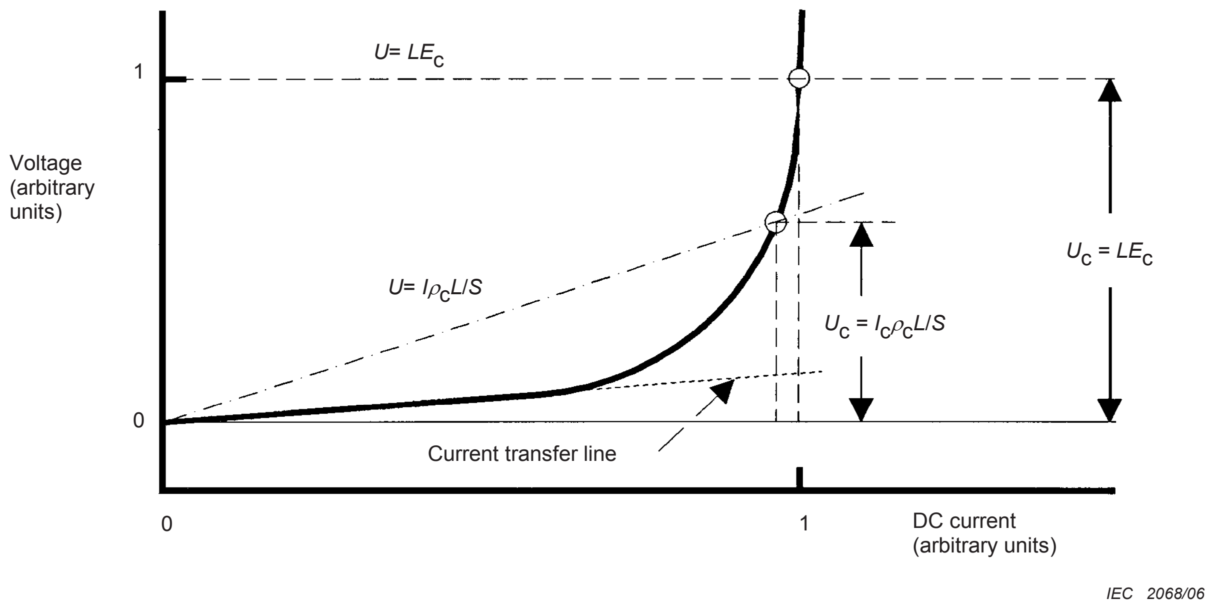
The *n*-value shall be calculated as the slope of the plot of log U versus log I in the region where the I_c is determined, or shall be calculated using two I_c values as determined in 10.1 at two different criteria.

The range of the criteria used to determine n shall be reported.



NOTE The application of the electric field and resistivity criteria to determine the critical current is shown.

Figure 1 – Intrinsic *U-I* characteristic



NOTE The application of the electric field and resistivity criteria to determine the critical current on a *U-I* characteristic, with a current transfer component exhibited as a linear region at low current is shown.

Figure 2 – *U-I* characteristic with a current transfer component

11 Test report

11.1 Identification of test specimen

The test specimen shall be identified, if possible, by the following:

a) name of the manufacturer of the specimen;
b) classification and/or symbol;
c) lot number;
d) raw materials and their chemical composition;
e) shape and area of the cross-section of the wire, number of filaments, diameter of filaments, twist pitch and copper/superconductor ratio.

11.2 Report of I_c values

The I_c values, along with their corresponding criteria, shall be reported.

11.3 Report of test conditions

The following test conditions shall be reported:

a) test magnetic field and uniformity of field;
b) test temperature;
c) number of turns of the tested coil;
d) technique used to wind the coil;
e) length between voltage taps and total specimen length;
f) shortest distance from a current contact to a voltage tap;
g) shortest distance between current contacts;
h) soldered length of the current contacts;
i) specimen bonding method, including identification of bonding material;
j) mandrel material;
k) mandrel diameter;
l) depth, shape, pitch and angle of grooves.

Annex A
(informative)

Additional information relating to the standard

A.1 Scope

There are a large number of variables that have a significant effect on the measured value of critical current which need to be brought to the attention of the user. Some of these will be addressed in this informative annex.

The method described in this standard is not applicable to wires with a copper/superconductor ratio (i.e. a volume ratio of Cu/Nb-Ti) that is smaller than 1, because the observed voltage-current (*U*-*I*) characteristics may not be stable at low magnetic fields.

The reason for the restrictions in this test method is to obtain the necessary uncertainty in the final definitive phase of long conductor qualification.

This standard requires that the specimen is to be tested while immersed in liquid helium that is near the boiling point of liquid helium at the normal atmospheric pressure of the test site. Testing in liquid helium at temperatures other than near this normal boiling point or testing in a gas or a vacuum is not covered by the scope of this standard.

A.2 Requirements

The d.c. critical current intended to be determined by the present method is the maximum direct electric current below which a superconductor can be regarded as resistance-less, at least for practical purposes, at a given temperature and magnetic field.

Typically, the upper limit of the test magnetic field (0,7 of the upper critical magnetic field) will be 8 T at a temperature near 4,2 K.

The minimum total length of the specimen is 210 mm, which represents the sum of the following:

– soldered length of current contacts (2 × 40 mm);
– distance between current and voltage contacts (2 × 40 mm);
– the minimum voltage tap separation (50 mm).

In the case of routine tests where it is impractical to adhere to these specific restrictions, this standard can be used as a set of general guidelines with an anticipated increase in uncertainty.

For routine tests, a wider range of parameters is accepted, but in definitive intercomparisons and performance verification, restrictions are needed to balance ease of use and resulting target uncertainty.

Measurements on short, straight specimens are considered acceptable practice for routine measurements if the cross-sectional area of the specimen is small in comparison with its length. However, for simplicity, this specimen geometry is omitted.

Measurements on non-inductively wound (bifilar) specimens in combination with epoxy specimen bonding are expected to give an uncertainty similar to the target uncertainty of this method. However, for simplicity, this specimen geometry is omitted. For a bifilar specimen geometry, the Lorentz force is away from the measurement mandrel for part of the specimen's length, and silicone vacuum grease or tension is not strong enough to keep the specimen from moving in this case.

Measurements on a non-ferromagnetic stainless steel mandrel combined with the use of solder to bond the specimen to the mandrel is considered acceptable practice for routine measurements. It will be difficult to estimate the amount of current shunted through the mandrel in this case, especially if a superconducting solder is used and the measurements are made in low magnetic fields.

When a magnetic field direction study is requested on a specimen with a rectangular cross-sectional area, there are two options. All field angles are possible by measuring a straight specimen geometry in a radial access magnet. Two field angles (0° and 90°) are possible by measuring a hairpin specimen geometry and a coiled specimen geometry in a solenoid magnet. Neither the straight nor the hairpin specimen geometry method is covered here.

The target uncertainty of the method described in this standard is defined by the results of an interlaboratory comparison. Results from previous interlaboratory comparisons were used in this test method to formulate the tolerances of the many variables that affect the uncertainty of critical current measurements. The target uncertainty, for an interlaboratory comparison, is a coefficient of variation (standard deviation divided by the average of critical current determinations) that is less than 3 %.

The coefficient of variation provides additional information on the expected distribution of results from a large number of determinations. However, if there are significant systematic errors, the measurements of two laboratories may differ by two or more times the coefficient of variation.

The expected and accepted uncertainty of critical current measurements at magnetic fields in the order of 0,8 times the upper critical field (around 9 T at 4,2 K) will have a higher coefficient of variation due to the increased sensitivity of I_c to magnetic field, temperature, strain and required voltage sensitivity.

It is expected that the uncertainty of the magnetic field in this test method may be the single most significant contributor to the overall uncertainty of the critical current measurement. However, a more restrictive tolerance may not be achievable due to the difficulty in calibrating this parameter.

The test method for determining the I_c values of superconducting composite wires excluded from the present test method may be addressed in future documents.

A.3 Apparatus

A.3.1 Measurement mandrel material

The following materials are recommended for measurement mandrel material. There is, however, no restriction on using other materials as long as they satisfy the criteria mentioned in 6.1.

Insulating material:

– fibreglass epoxy composite, with the specimen lying in the plane of the fabric;
– fibreglass epoxy composite tube fabricated from a plate stock so that the planes of the fabric are perpendicular to the axis of the tube;
– thin-walled rolled fibreglass epoxy composite tube.

Conductive non-ferromagnetic material covered with an insulating layer:

– non-ferromagnetic copper alloy, such as brass;
– non-ferromagnetic stainless steel.

Conductive non-ferromagnetic material without an insulating layer:

– non-ferromagnetic stainless steel;
– Ti-5 mass % Al-2,5 mass % Sn, with the limitation that this material is superconductive at temperatures below 3,7 K.
– copper alloys like brass (Cu-Zn) and cupronickel (Cu-Ni).

The leakage current through a conductive mandrel without an insulating layer can be estimated by making measurements under test conditions with and without a specimen on the mandrel. The measurement of voltage drop from current contact to current contact without a specimen and under test conditions can be used to estimate the resistance of the leakage path including contact resistance. Then, the measurement of voltage drop from current contact to current contact with a specimen and under test conditions can be used to estimate the leakage current.

It is possible to have a significant leakage current through a conductive mandrel when measuring conductors that are thermally unstable [2]. A section of the conductor outside the regular voltage taps can switch to the normal state, causing significant leakage current, a lowering of the actual net current through the specimen, and highly misleading results. This can easily be detected by monitoring and recording the voltage on a pair of diagnostic taps that measure the voltage between the current contacts to the specimen.

A.3.2 Mandrel construction

If a helical groove is chosen, it is recommended that the groove depth be at least half the wire diameter for a round wire or at least half the thickness for a rectangular wire. Typically, the groove for a round wire is V-shaped and the groove for a rectangular wire is rectangular-shaped.

A 7° pitch angle corresponds to a pitch of 9 mm for a 24 mm mandrel diameter.

Typically, the current contacts are made from cylindrical copper rings as shown in Figure A.1 and the outer diameter of the ring should be close to the inner diameter of the coiled specimen to minimize bending strain.

Typically, a higher current capacity superconductive lead is used to carry current to and from the current contact to reduce the heat load near the ends of the specimen.

Superconductive leads may be wrapped partway around the copper rings to reduce the effective contact resistance. If the critical current of the superconductive lead is much larger than that of the specimen under test conditions, then the lead should not cover more than 90 % of the circumference of the copper ring.

A.4 Specimen preparation

A.4.1 Specimen bonding

Specimen motion can result in a premature quench (irreversible thermal runaway), voltage noise and ultimately a reduction in the repeatability of critical current.

Winding tension can provide adequate specimen support depending on the differential thermal contraction between the specimen and the measurement mandrel.

Although a low temperature adhesive can help reduce the likelihood of a quench, too much adhesive can cause a quench by inhibiting the heat flow from the specimen to the helium bath.

A rough and clean surface on the measurement mandrel and a clean surface on the specimen is needed for strong specimen bonding.

It is impractical to specify a single specimen bonding technique for all conductors and measurement mandrel materials.

The use of solder to bond the specimen to the measurement mandrel between the current contacts is not allowed for reasons of difficulty in estimating leakage current, artificially increasing stability and amplified differential thermal contraction.

However, in any specimen bonding technique, an excessive temperature rise of the specimen may be considered.

A.4.2 Specimen mounting

The cross-sectional area of the conductor is measured before it is mounted and this area is used in the determination of I_c when a resistivity criterion is used. A combined standard uncertainty of 2,5 % is sufficient for the determination of I_c and ρ_c; however, a combined standard uncertainty not in excess of 0,5 % may be needed when a critical current density J_c determination is desired.

The coil is wound with the same curvature as the natural curvature set from spooling.

In general, one end of the wire is anchored. Winding tension is applied to the specimen. The other end is anchored. The current contacts are then soldered.

Multiple turns soldered to the current contact can cause a slowly decaying magnetic field. This magnetic field is produced by the current induced by a change in the background magnetic field set point.

The specimen support structure is needed to hold the specimen in the centre of the background magnet in a liquid helium cryostat, and to support current and voltage leads between room and liquid helium temperatures.

To reduce thermoelectric voltages on the specimen voltage leads, copper voltage leads are used which are continuous from the liquid helium bath to room temperature where an isothermal environment for all room temperature joints or connections is provided. It should be noted that the joints or connections immersed in liquid helium are isothermal.

A.5 Measurement procedure

A quench protection circuit or a resistive shunt may be necessary to protect the specimen from damage caused by the specimen current in the event that the specimen enters the normal state.

One method of *U-I* data acquisition, called constant sweep rate method, is to sweep the current at a constant rate from zero to a current that is just a little above I_c. The ramp rate limitations in Clause 8 are due to considerations of inductive voltage and specimen heating.

The inductive voltages at the upper end of the allowed ramp rates may not be constant with current, depending on ramp rate, voltage sensitivity, quench history of the specimen, and when the background field was last changed [3]. These variable inductive voltages can appear to be current transfer voltages and can limit the validity of the measurement in 10.1. This effect may be reduced in subsequent measurements by first cycling the current up to I_c and back to zero after any change in the applied magnetic field or after the specimen has quenched.

A second method of *U-I* data acquisition, called the ramp and hold method, is to ramp the current to a number of appropriately distributed points along the curve and hold the current constant at each of these points while acquiring a number of voltage and current readings. A faster ramp rate is allowed between each current set point in this case. However, a short settling time is needed after each fast current ramp.

Settling times as long as 3 s may be necessary depending on ramp rate, voltage sensitivity, quench history of the specimen, and when the background field was last changed [3]. This effect may be reduced in subsequent measurements by first cycling the current up to I_c and back to zero after any change in the applied magnetic field or after the specimen has quenched.

If the system noise is significant compared to the prescribed value of voltage, it is desirable to increase the time for the ramp from zero current to I_c to more than 150 s in order to allow more time for data averaging. In this case, care should be taken to increase the heat capacity and/or cooling surface of the current contacts enough to suppress the influence of heat generation due to the longer time required for the measurement. It should be noted that the step and hold current method allows for averaging data which can be appropriately distributed along the *U-I* characteristic.

With time, ramping the specimen current can induce a positive or negative voltage on the voltage taps. This source of interfering voltage during the ramp can be identified by its proportional dependence on ramp rate. If this voltage is significant compared to U_c, then decrease the ramp rate, decrease the area of the loop formed by the voltage taps and the specimen between them, or else use the step and hold current method.

Notice that stick-slip or continuous specimen motion can occur during the ramp due to the increasing Lorentz force with time. If this source of interfering voltage is significant compared to U_c, then check the direction of the Lorentz force, improve the specimen support or thermal stability, or use the ramp and hold current method.

If the *U-I* characteristic is not valid, the repeatability may be improved by improving the quench protection of the specimen. Changes can also be made to improve the specimen support or thermal stability (which might have longer current contacts and less adhesive on the outer surface of the specimen).

The baseline voltage may include thermoelectric, off-set, ground loop and common mode voltages. It is assumed that these voltages remain relatively constant for the time it takes to record each *U-I* characteristic. Small changes in thermoelectric and off-set voltages can be approximately removed by measuring the baseline voltage before and after the *U-I* curve measurement and assuming a linear change with time. If the change in the baseline voltage is significant compared to U_c, then corrective action to the experimental configuration should be taken.

Variations in ground loop and common-mode voltages can be irregular functions of specimen current and thus, if they are large, action should be taken to reduce them. This is difficult to distinguish from a current transfer voltage and would limit the validity of the measurement through the current transfer limit. A test for common-mode problems can be performed by measuring a null voltage tap pair (see Figure A.1) as a function of specimen current. A non-zero voltage measured on this pair should not be a function of specimen current, although it may be a function of current sweep rate. If it is a function of current, this will indicate the level of the problem.

A.6 Uncertainty of the test method

An optional method for assessing the overall uncertainty of a laboratory's critical current measurement system is to obtain and measure the standard reference material SRM-1457 which is available from:

National Institute of Standards and Technology
Standard Reference Materials Program
100 Bureau Drive, Stop 2322
Gaithersburg, MD 20899-2322
U.S.A.

Telephone:(301)975-6776
Fax:(301)948-3730
srminfo@nist.gov
http://www.nist.gov/srm

It is valid to measure the SRM with the present test method together with the precaution on the SRM certificate (i.e. the present test method may be substituted for the ASTM test method listed on the certificate).

The size and complex dependence of the self-field effect on current, coil diameter, pitch, etc. may result in a detectable systematic effect, but is not expected to be significant compared to the target uncertainty for an interlaboratory comparison on nearly identical specimens. However, a rough estimation of the self-field effect on I_c can be made, if necessary, using the information contained in the test report. See Annex B for a further discussion of the self-field effect.

A quench protection circuit that resets the specimen current to zero when the specimen voltage exceeds a trip point may be necessary to allow additional determinations of critical current.

A.7 Calculation of results

A.7.1 Critical current criteria

For some applications, the Nb-Ti cross-sectional area is used in the resistivity criterion. This area is usually determined by a measurement of the Cu to Nb-Ti ratio using the weighing, etching and weighing method. A corresponding standard test procedure is available (see IEC 61788-5 [4]).

When the criterion of 10^{-14} Ωm is adopted, the distance between voltage taps may need to be greater than 500 mm to increase the signal-to-noise ratio.

A larger separation between current and voltage connections may be necessary if a significant current transfer component exists relative to the criteria.

A.7.2 *n*-value (optional calculation)

The superconductor's *U*-*I* characteristic can usually be approximated by the empirical power-law equation:

$$U = U_0 \, (I/I_0)^n \tag{A.1}$$

where

U is the specimen voltage, in microvolts (μV);

U_0 is a reference voltage, in microvolts (μV);

I is the specimen current, in amperes (A);

I_0 is a reference current, in amperes (A).

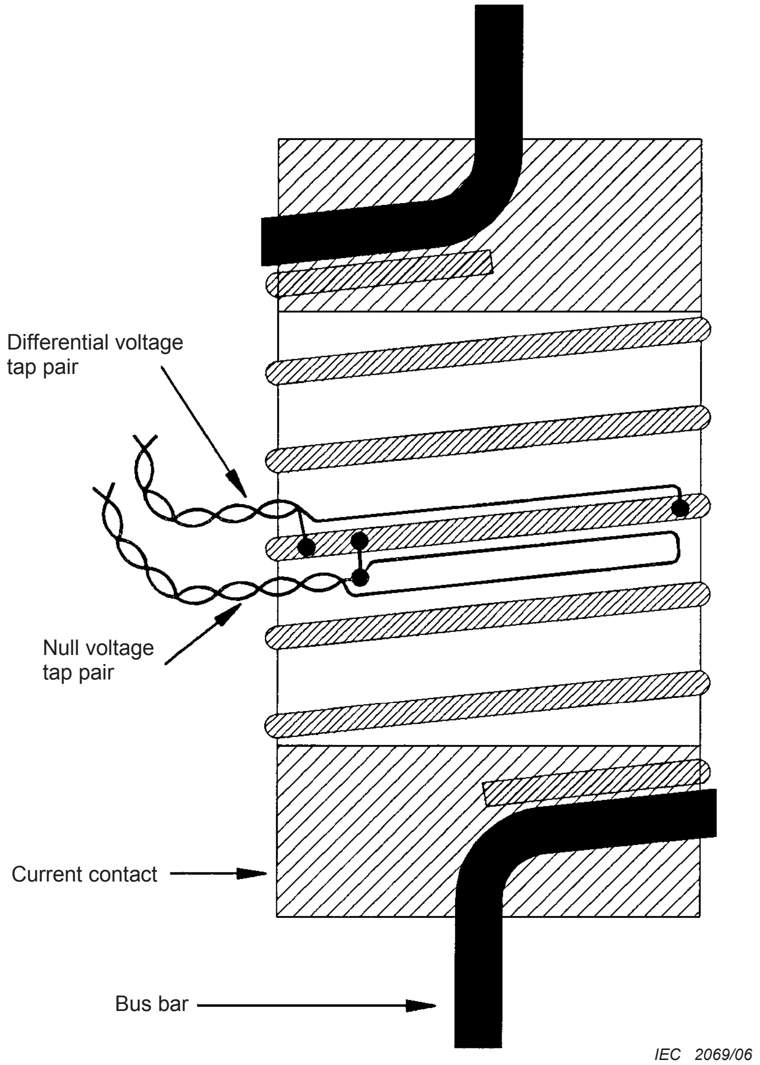
The *n*-value (no units) reflects the general shape of the curve.

A plot of log U versus log I is not always linear, even in the current range near the critical current criterion E = 10 μV/m, thus the range of the criteria used to determine n needs to be reported. Typically this range is 10 μV/m to 100 μV/m or 10^{-14} Ωm to 10^{-13} Ωm.

The scatter in the determined values of n may have a coefficient of variation as large as 20 %, therefore the procedure for determining the *n*-value is optional in the present method.

Other effects that may contribute to the variability of the *n*-value are the following:

- voltage noise;
- current ripple;
- specimen cooling (amount of adhesive used or extra stability from an un insulated conductive mandrel);
- magnetic field ripple and uniformity;
- self-field of the specimen current;
- a thermal gradient on the specimen.



NOTE The null voltage tap pair is used for the detection of ground loop or common-mode voltage problems. The differential voltage tap pair (shown here over a short length for clarity) is left undisturbed while a separate pair is attached to the specimen as shown, with one lead of the pair shorted to the other one which is still connected to the specimen. The null voltage tap pair is configured with a small loop of wire to simulate the mutual inductance of the differential voltage tap pair. The voltage measured on the null voltage tap pair should not be a function of specimen current, although it may be a function of current sweep rate. If it is a function of current, this indicates the level of the problem.

Figure A.1 – Instrumentation of specimen with a null voltage tap pair

Annex B
(informative)

Self-field effect

Because of the high current flowing through a coiled specimen, the specimen will generate its own magnetic field, giving rise to the self-field effect on the measured critical current. This self-field is generated in addition to the applied magnetic field, so the total field experienced by the specimen is greater than the applied magnetic field for a portion of the cross-sectional area of the conductor. Some laboratories make an approximate correction for this additional self-field.

In an interlaboratory comparison of critical current measurements, a self-field correction would unnecessarily compromise the I_c data, since each laboratory's specimen would experience nearly the same self-field effect. There would only be a difference in the self-field effect due to the diameter and pitch of the measurement mandrel (which is controlled in an interlaboratory comparison) and in the homogeneity of the applied magnetic field. Because the specimens are nearly identical in an interlaboratory comparison, there is little need to make an approximate correction for the self-field effect. Critical current data that are "corrected" for the self-field effect by some laboratories participating in the interlaboratory comparison and not by others yield incomparable results. Thus, it may be better to omit critical current self-field corrections in interlaboratory comparisons.

This does not diminish the need and utility of a self-field correction to compare critical current densities of different diameter wires. When making comparisons of the critical current densities of different diameter wires, the self-fields experienced by the conductors are different, and should be corrected. The current densities after the self-field correction would yield more comparable data. An approximate correction is based on the magnetic field of a long straight wire:

$$B_{SF} = \mu_0 I/(2\pi r) \quad \text{(B.1)}$$

where

B_{SF} is the approximate self-field, in teslas (T);

μ_0 is the magnetic permeability of a vacuum, $4\pi \times 10^{-7}$ H/m;

I is the current, in amperes (A);

r is the radius of the wire, in metres (m).

This equation can also be written as follows:

$$B_{SF} = (4 \times 10^{-4})\ I/d \quad \text{(B.2)}$$

where

B_{SF} is the approximate self-field, in teslas (T);

I is the current, in amperes (A);

d is the wire diameter, in millimetres (mm).

This approximate correction has been shown to resolve partially the difference between transport J_c measurements and calculations using d.c. magnetization measurements, and to correct J_c measurements on wires with different diameters in J_c optimization studies. It has also been used to correlate wire and cable critical current measurements with magnetic performance. This method of correction was selected for presentation here because of its simplicity, wide range of application and demonstrated effectiveness. The approximation given by equation (B.1) does not include considerations such as the copper superconductor ratio, the resistivity of the matrix, the twist-pitch of the filament, filament distribution, current redistribution among the filaments or the diameter and helical pitch of the measurement mandrel.

This approximate correction is generally considered to be accurate enough for its intended purpose as long as the measurement parameters do not enhance the self-field effect. However, this correction is not accurate enough for an interlaboratory comparison. Any correction that includes some of the parameters that may be different among laboratories in an interlaboratory comparison would be extremely complex and still might not be as accurate as necessary. Since this approximate self-field correction does not incorporate effects due to the measurement mandrel diameter and helical pitch, steps should be taken to reduce the contribution of these parameters on critical current measurements that will be used in critical current density comparisons. This implies that larger diameter (>30 mm) measurement mandrels with a pitch angle closer to 7° should be used for high current specimens (>300 A) or for measurements in low magnetic fields (<3 T) where the critical current is more dependent on magnetic field. More definitive guidelines would require additional research on these effects. Self-field effects are difficult to study because the transport critical current cannot be measured without some self-field and the effect of bending strain on critical current is also convoluted with the self-field effect in many experiments.

An expedient method of reducing the influence of the self-field during an interlaboratory comparison is to standardize the diameter and pitch of the measurement mandrel. The reality of this approach is that the choice of parameters tends toward the smallest diameter, which may be appropriate for the interlaboratory comparison but impractical for routine current-density measurements. A single standard measurement mandrel appropriate for the range of conductors in this standard would be impractical because the mandrel diameter appropriate for the largest conductor would not fit into the access bore of magnets used by many laboratories.

Another method that is sometimes used to normalize part of the self-field effect is to average critical currents for currents flowing in both directions. This may reduce the effect of the diameter of the specimen measurement mandrel and the winding pitch. However, this correction method does not apply to the present measurement standard because the measurement standard does not allow for reversal of current direction.

Annex C
(normative)

Test method for Cu/Cu-Ni/Nb-Ti composite superconductors

C.1 General

This annex covers the exceptions for Cu/Cu-Ni/Nb-Ti composite superconductors, while the main part of this standard can be used for both Cu/Nb-Ti and Cu/Cu-Ni/Nb-Ti superconductors. The subclauses of Clause C.2 replace the referencing requirements in the main part of the standard for Cu/Cu-Ni/Nb-Ti specimens.

C.2 Exceptions for Cu/Cu-Ni/Nb-Ti composite superconductors

C.2.1 The specimen shall be affixed to the measurement mandrel with a tension corresponding to the total strain larger than 0,1 % and less than 0,2 %. (Low temperature adhesives shall be avoided, except Apiezon® type high thermally conductive grease as noted in C.5.)

C.2.2 The target uncertainty of this method is defined as a coefficient of variation (COV; standard deviation divided by the average of the critical current determinations), that shall not exceed 3 %. In order to get a COV less than 2 %, the direction of Lorentz force shall be radially outward on the coiled specimen.

C.2.3 Suitable mandrel materials are recommended in Annex A. Any one of these may be used; however, fiberglass epoxy composite with the specimen lying in the plane of the fabric is recommended.

C.2.4 When a conductive material is used without an insulating layer, especially when the specimen is bonded with solder, the leakage current through the mandrel shall be less than 0,2 % of the total current when the specimen current is at I_c that is determined using the lowest critical current criterion being reported (see 9.5 and A.3.1).

C.2.5 Specimen shall be wound on the measurement mandrel by using tension only. Use of low temperature adhesives shall be avoided. Silicon grease for vacuum apparatus strongly increases the likelihood of a quench, and thus, shall not be used. Although a high thermally conductive grease like Apiezon® can help reduce the likelihood of a quench, a minimum amount shall be used if it determined to be necessary.

C.2.6 The use of solder to bond the specimen to the measurement mandrel is allowed, but in this case, the critical current criteria of 10 μV/m and 10^{-14} Ωm are valid and both higher criteria (100 μV/m and 10^{-13} Ωm) are invalid.

C.2.7 To ensure that the specimen is well-seated in the groove and to reduce the likelihood of a quench, a tensile force shall be applied to the wire during winding, and this force shall not result in more than 0,2 % total strain on the wire. This force shall be adjusted to the range of 0,1 % to 0,2 % total strain on the specimen (see Annex D).

C.2.8 The direction of the current and the applied magnetic field shall result in an outward Lorentz force over the length of the specimen between the voltage taps.

Annex D
(informative)

Guidance for estimating winding tensile force

This annex gives guidance and an example of estimating the winding tensile force necessary in order to be within the strain limits. The tensile strain needs to be sufficiently high to reduce specimen motion, but not so high that it degrades the critical current. The strain limits are different for Cu/Nb-Ti (see 7.2) and for Cu/Cu-Ni/Nb-Ti (see Clause C.7). This is not intended to accurately determine the tensile strain of the specimen.

The stress-strain relationship in the elastic limit (strains less than 0,2 % are likely within the elastic limit) is approximately:

$$\sigma = E\,\varepsilon \tag{D.1}$$

where

σ is the stress, in pascals (Pa) or (N/m^2);

E is the modulus of elasticity, in pascals (Pa) or (N/m^2);

ε is the strain (change in length divided by original length), which is dimensionless.

Typical values of E for various materials are given in Table D.1. For a composite superconductor, the composite's modulus of elasticity can be estimated using the "rule-of-mixtures:"

$$E_{comp} = f\,E_{sc} + (1 - f)\,E_m \tag{D.2}$$

where

E_{comp} is the composite's modulus of elasticity, in pascals (Pa) or (N/m^2);

f is the volume fraction of superconductor, which is dimensionless;

E_{sc} is the superconductor's modulus of elasticity, in pascals (Pa) or (N/m^2);

E_m is the matrix's modulus of elasticity, in pascals (Pa) or (N/m^2).

The "rule-of-mixtures" can be extended to three component superconductors.

The following is an example to estimate the tensile force necessary to strain a 1 mm diameter wire by 0,1 % assuming f = 0,4 (40 % Nb-Ti) and the matrix is Cu (60 % Cu). Using this f and the values in Table D.1 for $E_{Nb\text{-}Ti}$ and E_{Cu}, the E_{comp} is estimated using equation D.2 to be 99,6 GPa. Substituting this E and ε = 0,001 into equation D.1 gives a σ (stress) of 99,6 MPa. The tensile force is:

$$F = \sigma\,S \tag{D.3}$$

where

F is the tensile force, in newtons (N);

S is the cross-sectional area of the wire, in square metres (m^2).

Substituting a stress of 99,6 MPa and the cross-sectional area of the wire (0,785 × 10^{-6} m^2) into equation D.3 gives a tensile force of about 78 N.

Table D.1 – Typical values of *E* at room temperature for various materials

Material	**Modulus of elasticity** GPa
Nb-48 mass % Ti	60
Cu	126
Cu-10 mass % Ni	122

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[1] IEC 60050-121*, International Electrotechnical Vocabulary – Part 121: Electromagnetism*

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[3] GOODRICH, LF. and STAUFFER, TC. *Advances in Cryogenic Engineering,* 2002, Vol. 48B, pp. 1142-1149.

[4] IEC 61788-5, *Superconductivity – Part 5: Matrix to superconductor volume ratio measurement – Copper to superconductor volume ratio of Cu/Nb-Ti composite superconductors*

NOTE Harmonized as EN 61788-5:2001 (not modified).

Annex ZA
(normative)

Normative references to international publications with their corresponding European publications

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.

NOTE When an international publication has been modified by common modifications, indicated by (mod), the relevant EN/HD applies.

Publication	Year	Title	EN/HD	Year
IEC 60050-815	-[1)]	International Electrotechnical Vocabulary (IEV) Part 815: Superconductivity	-	-

[1)] Undated reference.

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