INTERNATIONAL STANDARD

IEC 61788-3

First edition
2000-12

Superconductivity –

Part 3:
Critical current measurement –
DC critical current of Ag-sheathed Bi-2212 and Bi-2223 oxide superconductors

Supraconductivité –

Partie 3:
Mesure du courant critique –
Courant critique continu des oxydes supraconducteurs Bi-2212 et Bi-2223 avec gaine en argent

Reference number
IEC 61788-3:2000(E)

Publication numbering

As from 1 January 1997 all IEC publications are issued with a designation in the 60000 series. For example, IEC 34-1 is now referred to as IEC 60034-1.

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Commission Electrotechnique Internationale
International Electrotechnical Commission
Международная Электротехническая Комиссия

PRICE CODE S

For price, see current catalogue

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

SUPERCONDUCTIVITY –

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FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
2) The formal decisions or agreements of the IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested National Committees.
3) The documents produced have the form of recommendations for international use and are published in the form of standards, technical specifications, technical reports or guides and they are accepted by the National Committees in that sense.
4) In order to promote international unification, IEC National Committees undertake to apply IEC International Standards transparently to the maximum extent possible in their national and regional standards. Any divergence between the IEC Standard and the corresponding national or regional standard shall be clearly indicated in the latter.
5) The IEC provides no marking procedure to indicate its approval and cannot be rendered responsible for any equipment declared to be in conformity with one of its standards.
6) Attention is drawn to the possibility that some of the elements of this International Standard may be the subject of patent rights. The IEC shall not be held responsible for identifying any or all such patent rights.

International Standard IEC 61788-3 has been prepared by IEC technical committee 90: Superconductivity.

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

FDIS	Report on voting
90/80/FDIS	90/86/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 3.

Annexes A and B are for information only.

The committee has decided that the contents of this publication will remain unchanged until 2005. At this date, the publication will be

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

A bilingual version of this standard may be issued at a later date.

INTRODUCTION

In 1986 J.G. Bednorz and K.A. Mueller discovered that some Perovskite type Cu-containing oxides show superconductivity at temperatures far above those which metallic superconductors have shown. Since then, extensive R & D work on high-temperature oxide superconductors has been and is being made worldwide, and its application to high-field magnet machines, low-loss power transmission, electronics and many other technologies is in progress [1].[1]

Fabrication technology is essential to the application of high-temperature oxide superconductors. Among high-temperature oxide superconductors developed so far, BiSrCaCu oxide (Bi-2212 and Bi-2223) superconductors have been the most successful at being fabricated into wires and tapes of practical length and superconducting properties. These conductors can be wound into a magnet to generate a magnetic field of several tesla [2]. It has also been shown that Bi-2212 and Bi-2223 conductors can substantially raise the limit of magnetic field generation by a superconducting magnet [3].

In summer 1993, VAMAS-TWA16 started working on the test methods of critical currents in Bi-oxide superconductors. In September 1997, the TWA16 worked out a guideline (VAMAS guideline) on the critical current measurement method for Ag-sheathed Bi-2212 and Bi-2223 oxide superconductors. This pre-standardization work of VAMAS was taken as the base for the IEC standard, described in the present document, on the d.c. critical current test method of Ag-sheathed Bi-2212 and Bi-2223 oxide superconductors.

The test method covered in this International Standard is intended to give an appropriate and agreeable technical base to those engineers working in the field of superconductivity technology.

The critical current of composite superconductors like Ag-sheathed Bi-oxide 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 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.

[1] The numbers in brackets refer to the bibliography.

SUPERCONDUCTIVITY –

Part 3: Critical current measurement – DC critical current of Ag-sheathed Bi-2212 and Bi-2223 oxide superconductors

1 Scope

This part of IEC 61788 covers a test method for the determination of the d.c. critical current of short and straight Ag- or Ag alloy-sheathed Bi-2212 and Bi-2223 oxide superconductors that have a monolithic structure and a shape of round wire or flat or square tape containing mono- or multicores of oxides.

This method is intended for use with superconductors that have critical currents less than 500 A and *n*-values larger than 5. The test is carried out with and without applying external magnetic fields. In the test of the tape specimen in magnetic fields, the magnetic fields are parallel or perpendicular to the tape surface. The test specimen is immersed either in a liquid helium bath or a liquid nitrogen bath during testing. Deviations from this test method that are allowed for routine tests and other specific restrictions are given in this standard.

Substantial parts of the test method covered in this standard are in common with, or similar to, those for Nb_3Sn composite superconductors (IEC 61788-2). Special features newly found for oxide superconductors may be classified into two groups. The first group is specific to oxide composite superconductors, including mechanical fragility originating from the presence of weak links, cryogen gas bubble formation, aging degradation, magnetic flux flow and creep, large anisotropy, hysteresis in critical current with magnetic field sweep, etc. The second group is due to the short length of the specimen used in the standard. A critical current measurement on such a specimen may easily pick up different voltage signals due to thermal electromotive force, inductive voltage, thermal noise, current redistribution, specimen motion relative to the holder, etc. Current transfer voltages may be present due to the short distance from a current contact to a voltage tap. Short specimen length may reduce mechanical tolerance against the Lorentz force, for example, by promoting the formation of cryogen gas bubbles within the composite.

2 Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this part of IEC 61788. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this part of IEC 61788 are encouraged to investigate the possibility of applying the most recent edition of the normative document indicated below. For undated references, the latest edition of the normative document referred to applies. Members of IEC and ISO maintain registers of currently valid International Standards.

IEC 60050-815:2000, *International Electrotechnical Vocabulary (IEV) – Part 815: Superconductivity*

IEC 61788-2:1999, *Superconductivity – Part 2: Critical current measurement – DC critical current of Nb_3Sn composite superconductors*

3 Terminology

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

3.1
critical current (I_c)
current at which a specified electric field strength (electric field) criterion (E_c) or resistivity criterion (ρ_c) is reached in the specimen at a certain value of a static applied magnetic field at a specified temperature either in a liquid helium bath or a liquid nitrogen bath at a constant pressure. For either E_c or ρ_c, there is a corresponding voltage criterion U_c for a specified sample length.

3.2

Bi-2212 and Bi-2223 oxide superconductors are defined in the chemical formulae as follows:

Bi-2212; $Bi_2Sr_2CaCu_2O_x$ (x = ~ 8),

Bi-2223; $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ (x = ~10).

4 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 target precision of this method is a coefficient of variation (standard deviation divided by the average of the critical current determinations) that is less than 5 % for the measurement at 0 T and near 4,2 K or 77 K.

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 current 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 energy stored in the superconducting magnets commonly used for the background magnetic field can cause similar large current and/or voltage pulses or deposit a large amount of thermal energy in the cryogenic systems causing rapid boil-off or even explosive conditions. The use of cryogenic liquids is essential to cool the superconductors, which allows the 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. It is imperative that safety precautions for handling cryogenic liquids be observed.

5 Apparatus

5.1 Measurement holder material

The measurement holder 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 critical current may inevitably depend on the measurement holder material due to the strain induced by the differential thermal contraction between the specimen and the measurement holder.

The total strain induced in the specimen at the measuring temperature shall be minimized to be within ±0,1 %. If there is an excess strain due to the differential thermal contraction of the specimen and the holder, the critical current shall be noted to be determined under an excess strain state by identification of the holder material.

Suitable measurement holder materials are recommended in A.4.1. Any one of these may be used.

When a conductive material is used without an insulating layer, the leakage current through the holder shall be less than 1 % of the total current when the specimen current is at I_c (see 8.5).

5.2 Measurement holder construction

The holder shall have a flat surface on which a straight specimen can be placed.

The current contact shall be rigidly fastened to the measurement holder to avoid stress concentration in the region of transition between the holder and the current contact. It is important to have no difference in level between the mounting surfaces of the current contacts and the mounting specimen holder.

6 Specimen preparation

6.1 Reaction heat treatment

Reaction heat treatment shall be carried out according to the manufacturer's specification which includes reaction temperature, period and atmosphere, oxygen partial pressure, specimen cooling and warming rates, specimen protection method against mechanical strain, examination of deformation and surface condition of specimen and error limits which must not be exceeded. Temperature variations within the furnace shall be controlled such as not to exceed those limits.

Reaction heat treatment can be skipped when it has already been carried out by the manufacturer.

6.2 Specimen mounting for measurement

After the reaction heat treatment, the ends of the specimen shall be trimmed to suit the measurement holder.

The specimen shall be mounted to the flat surface of the holder and both ends shall be soldered to the current contact blocks (see A.6 for solder material).

For the test in magnetic fields, a low-temperature adhesive (such as epoxy) shall be used to bond the specimen to the measurement holder to reduce specimen motion against the Lorentz force.

The bond shall be strong enough to keep the specimen in place against the Lorentz force, in the case where the applied magnetic field is perpendicular to the specimen surface.

The length of a specimen to be measured shall be defined as follows:

$$L_1 = 2 \times L_2 + L + 2 \times L_3 \geq 5 \times W \tag{1}$$

$$L_2, L, L_3 \geq W \tag{2}$$

where

L is the distance between the voltage taps;

L_1 is the length of a specimen to be measured;

L_2 is the length of the soldered part of the current contact;

L_3 is the distance from a current contact to a voltage tap;

W is the width or diameter of a specimen to be measured.

For a specimen with a large current-carrying capacity, L_2 shall be larger. L shall be larger for a measurement that needs high sensitivity and L_3 shall be larger when current transfer voltage cannot be neglected.

In the case of the wire specimen the angle between the specimen axis and the magnetic field shall be (90 ± 9)°. This angle shall be determined with an accuracy of ±2°.

In the case of tape specimens, there are two options in addition to the requirement that the angle between the longitudinal specimen axis and the magnetic field shall be (90 ± 9)°. In one option, the magnetic field shall be perpendicular to the specimen surface, the angle deviation being within ±7°. In the second option, the magnetic field shall be parallel to the specimen surface, the angle deviation being within ±3°.

The voltage taps shall be placed in the central part along both the specimen length and the specimen width.

All soldering shall be conducted as quickly as possible so as not to cause thermal damage to the specimen. Soft voltage leads shall be used and twisted before soldering.

The distance between the voltage taps, L, shall be measured to an accuracy of 5 %. This voltage tap separation shall be greater than the specimen width.

7 Measurement procedure

For testing, the specimen and the holder shall be mounted in a test cryostat consisting of a liquid helium or nitrogen dewar, a magnet (when necessary) and a support structure.

The specimen shall be immersed in cryogen for the data acquisition phase. The specimen may be cooled slowly in cryogen vapour, or inserted slowly into the cryogen bath, or, in the case of cooling to the 4,2 K range, first slowly immersed in liquid nitrogen and then liquid helium. The specimen shall be cooled from room temperature to liquid helium (or liquid nitrogen) temperature over a time period of at least 5 min.

Between each measuring temperature and each magnetic-field angle, the specimen shall be cooled in zero field, from a temperature above the critical temperature down to the measuring temperature, and then the field angle with respect to the conductor cross-section shall be fixed while the field is still zero. This procedural step can only be omitted if one of the following two conditions is met: only zero field measurements will be made with monotonically decreasing temperatures or the specimen has a demonstrated magnetic hysteresis of less than 2 % for the magnetic fields to be measured (see annex B).

The temperature of the cryogen bath shall be measured during each determination of I_c.

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

When using the constant sweep rate method, the current sweep rate shall be lower than 2 I_c per minute.

When using the step-and-hold current method, the current sweep rate between current set points shall be lower than 10 I_c per minute. The current drift during each current set point shall be less than 1 % of I_c.

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.

If the magnetic field is parallel to the surface of the measurement holder, the relative direction of the current to the applied magnetic field shall result in the Lorentz force which pushes the specimen against the surface of the measurement holder. In the case of the applied magnetic field perpendicular to the measurement holder surface, either direction of the current relative to the field is possible, with the condition that the specimen is rigidly mounted to the measurement holder with appropriate adhesive.

Record the *U-I* characteristic with increasing current and at monotonically increasing magnetic fields (see annex B).

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

8 Precision and accuracy of the test method

8.1 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 an accuracy of at least 0,5 %, shall be used to determine the specimen current.

A recorder and the 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 to a precision of 10 % and the corresponding current to an accuracy of 1 % and with a precision of 1 %.

8.2 Temperature

A cryostat shall provide the necessary environment for measuring I_c and the specimen shall be measured while immersed in liquid helium or liquid nitrogen. The liquid temperature shall be reported to an accuracy of ±0,1 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.

To convert the pressure observed in the cryostat into a temperature value, the phase diagram of helium or nitrogen shall be used. The pressure measurement shall be accurate enough to obtain the required accuracy of the temperature measurement.

8.3 Magnetic field

A magnetic system shall provide the magnetic field to an accuracy of 1 % and a precision of 0,5 %.

The magnetic field shall have a uniformity better than ±2 % over the length of the specimen between the voltage taps.

The maximum periodic and random deviation of the magnetic field shall be less than ±1 %.

For critical current measurements at zero or very low magnetic field, the residual magnetic field in a superconducting magnet shall be minimized.

8.4 Specimen and holder support structure

The support structure shall provide 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 a precision of 2 %.

8.5 Specimen protection

If a resistive shunt or a quench protection circuit is used in parallel with the specimen, then the current through the circuit shall be less than 1 % of the total current at I_c.

9 Calculation of results

9.1 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-sectional area S of the composite superconductor is preferred for the estimation of the resistivity (see figures 1 and 2).

In the case of the electric field criterion, two values of I_c shall be determined at criteria of 100 µV/m and 500 µV/m. In the other case, two values of I_c shall be determined at either of the resistivity criteria of 2×10^{-13} Ωm and 10^{-12} Ωm.

When it is difficult to measure the I_c properly at a criterion of 500 µV/m, an E_c criterion of less than 500 µV/m must be substituted. Otherwise, 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):

$$U_c = L\ E_c \tag{3}$$

where

U_c is the voltage criterion in microvolts (µV);

L is the voltage tap separation in meters (m);

E_c is the electric field criterion in microvolts/meter (µV/m);

or, when using a resistivity criterion:

$$U_c = I_c\ \rho_c\ L/S \tag{4}$$

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 total cross-sectional area in square meters.

A straight line shall be drawn from the baseline voltage to the average voltage near 0,5 I_c (see figures 1 and 2). A finite slope of this line may be due to current transfer and/or local sample damage. 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 100 µV/m or 2×10^{-13} Ωm.

9.2 *n*-value (optional)

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.

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

10 Test report

10.1 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 cores, diameter of cores, volume fractions of cores to Ag or Ag alloy sheath, and other components in the wire;

f) manufacturing process technique.

10.2 Report of I_c values

The I_c values, along with their corresponding criteria, and *n*-values (optional) shall be reported.

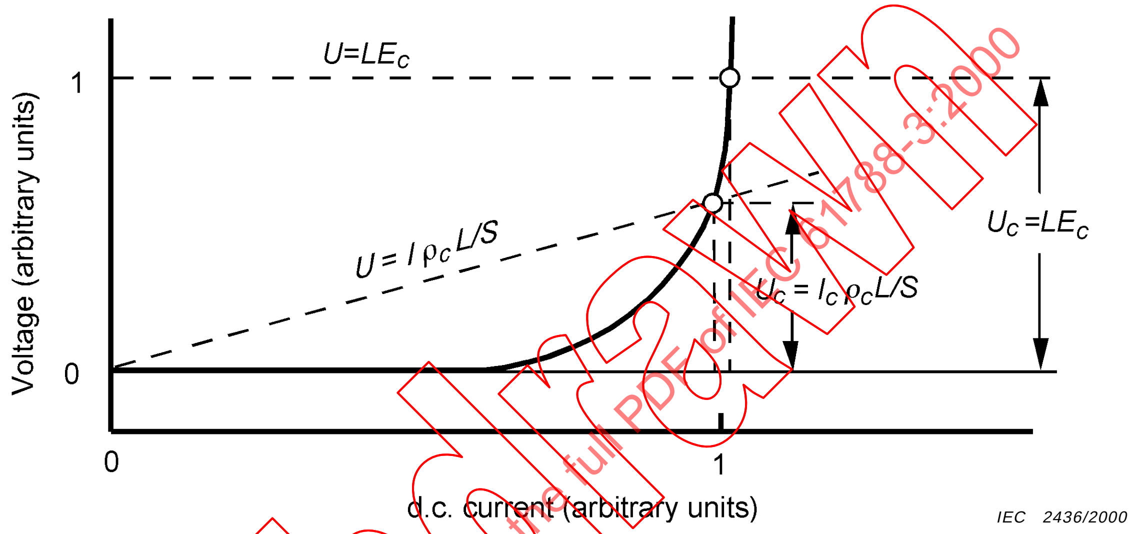
10.3 Report of test conditions

The following test conditions shall be reported:

a) test magnetic field strength, and orientation, uniformity and accuracy of field;

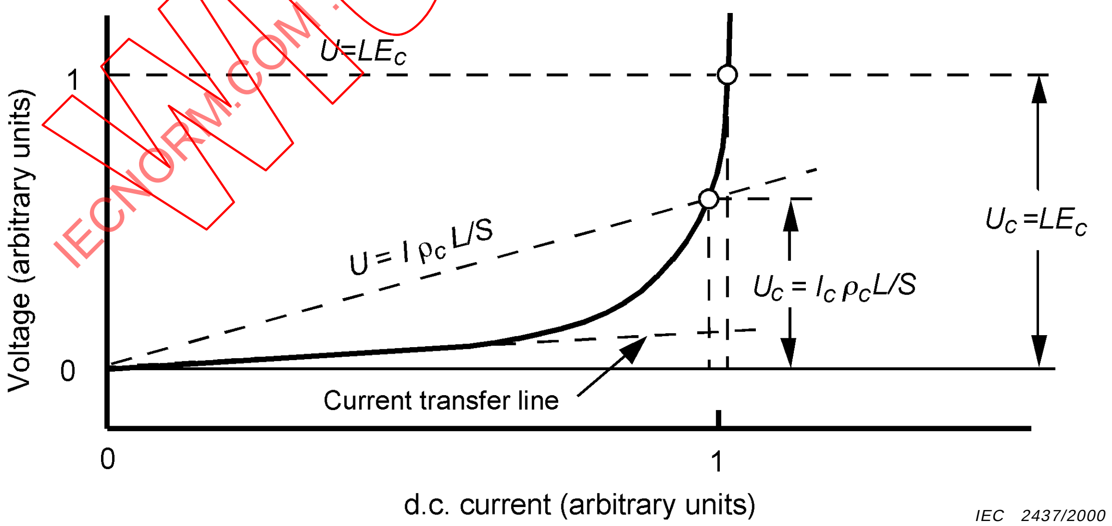
b) test temperature and accuracy of temperature;

c) length between voltage taps and total specimen length;
d) the shortest distance from a current contact to a voltage tap;
e) soldered length of the current contacts;
f) the specimen bonding method, including identification of the bonding material;
g) Lorentz force direction;
h) sample history with magnetic field sweep;
i) sample history with temperature variation;
j) sample history with current sweep and hold.



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

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 above.

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

Annex A
(informative)

Additional information relating to clauses 1 to 9

A.1 Scope

There are a large number of variables that have a significant effect on the measured value of critical current in Ag-sheathed Bi-2212 and Bi-2223 oxide superconductor wires and tapes. However, significant portions of the test method covered in this standard are common or similar to those for Nb_3Sn composite superconductors (IEC 61788-2). Thus, only part of these variables will be addressed in this informative annex. For those variables that are not mentioned here, refer to IEC 61788-2.

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

This standard assumes that measurements are made either in liquid helium or liquid nitrogen. However, it is generally accepted that, if these measurements can be made in liquid helium, then they can be made in other cryogens, such as liquid neon and liquid hydrogen, because the heat of vaporization of liquid helium is low compared to other cryogens. Thus, this standard should extend to measurements conducted in other cryogens.

Cryogens (including nitrogen, helium, neon, and hydrogen) are used at temperatures near boiling point for the normal atmospheric pressure of the test site. The use of cryogens at temperatures other than near boiling point, or measurements in a gas or a vacuum are not covered by the scope of this standard.

A.2 Terminology

The statements defining terms in this standard are practical/engineering definitions in the context of the measurement as opposed to the formal/scientific definitions in the terminology document.

A.3 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.

In this test method, a measurement holder is prepared.

The minimum total length of the tape specimen is five times the tape width (W), which represents the sum of the following:

– the soldered length of current contacts (2 W);

– the distance between current and voltage contacts (2 W);

– the minimum voltage tap separation (1 W).

The target precision of the method described in this standard is defined by the results of an interlaboratory comparison. Results from the previous VAMAS interlaboratory comparisons (the regional and the general intercomparisons) were used in this test method to formulate the tolerances of the many variables that affect the precision of critical current measurements. The target precision, for an interlaboratory comparison, is a coefficient of variation (standard deviation divided by the average of critical current determination) that is less than 5 % for the measurement at 0 T and near 4,2 K or 77 K.

It is expected that the specimen mounting and the specimen cooling procedures in this test method may be one of the most significant contributors to the overall uncertainty of the critical current measurement.

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 reduction in precision.

The test method for determining the I_c values of Ag-sheathed Bi-oxide superconductor wires and tapes excluded from the present test method may be addressed in future documents.

In the case of measurements made in liquid hydrogen, additional safety precautions may be required since hydrogen leakage into air can result in accidental gas explosion.

A.4 Apparatus

A.4.1 Measurement holder material

In this method, the specimen strain is controlled to a minimum (less than 0,1 %). A 0,1 % thermal contraction may result in no appreciable I_c deviation at 0 T and near 4,2 K or 77 K. One significant source of strain is the mismatch in thermal contraction rates between the measurement holder and the specimen when cooled to liquid helium or nitrogen temperature.

Based on the typical thermal contractions shown in table A.1, the following materials are suggested for the measurement holder material. For alternate holder materials, a carefully prepared qualification study should precede the routine tests.

Recommended holder material:

– fibreglass epoxy composite, with the specimen lying in the plane of the fabric wrap;

– ceramic dispersed epoxy;

– Ag/Ag alloy.

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

A.4.2 Measurement holder construction

An example of a measurement holder is shown in figure A.1. Typically, the current contacts are made from copper blocks, and the thickness of the contact should be determined so that there will be no difference in level between the specimen and the contact surfaces; the contact blocks need to be rigidly affixed to the holder.

A.5 Specimen preparation

A.5.1 Specimen mounting for measurement

Extreme care must be taken in trimming and mounting the specimen after the reaction so as not to damage the specimen.

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

It is recommended that a low-temperature adhesive, such as epoxy, be used to secure the specimen to the holder.

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

The low-temperature adhesive should be resistant to soldering heat while soldering.

The low-temperature adhesive should be a thin layer between the specimen and the holder surface.

After the low-temperature adhesive is applied, the specimen should be pressed to the holder with a pressure that does not damage the specimen.

The distance between the voltage taps is defined as the smallest distance between the soldered leads, irrespective of the sizes of the solder spots.

A.6 Measurement procedure

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

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

As soldering material, Indium, Indium alloys or Bismuth alloys with a low melting temperature are preferable, although usual Pb-60 % Sn and Pb-70 % Sn are also applicable.

The specimen cooling rate may affect the measured critical current. The strength of the bond between the specimen and its holder changes during the cooling process when differential thermal contraction between the specimen and the holder is also occurring. This may result in disabling the low-temperature adhesive.

Oxygen impurities can cause boiling temperature variation of liquid nitrogen in the test cryostat if it is not tightly sealed.

If the system noise is significant compared to the prescribed value of voltage, it is desirable to decrease the sweep rate to less than 0,4 I_c/min 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.

Ramping the specimen current can induce a positive or negative voltage on the voltage taps with time. 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.

Faster current ramp rates can be used for the step and hold current method if the measurement system proves to yield consistent results with the specified ramp rate of 10 I_c/min. It is possible to obtain consistent results with ramp rates as high as 500 A/s on a conductor with critical current from 10 A to 200 A.

Specimen motion can induce spike noises. The specimen holder should be tightly mounted to the support structure, while the support structure should be held rigid against the magnetic field.

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.

For critical current measurements at zero or very low magnetic fields, the residual magnetic field in a superconducting magnet shall be completely minimized or the use of a superconducting magnet shall be avoided. This is especially important for the measurements near liquid nitrogen temperature.

A.7 Precision and accuracy of the test method

An optional method for partially assessing the overall precision of a laboratory's critical current measurement system is to obtain and measure a superconductor simulator (figure A.2) originally developed at the National Institute of Standards and Technology, Boulder, Colorado, USA.

A.8 Calculation of results

A.8.1 Critical current criteria

For some applications, the non-Ag (or non-Ag alloy) cross-sectional area is used in the resistivity criterion. It can be determined by using a graphical analysing method.

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

A.8.2 *n*-value

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

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

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.

Table A.1 – Thermal expansion data of Bi-oxide superconductor and selected materials

Material		**Thermal expansion** %							
		Temperature K							
		273	200	150	100	50	20	10	4
Bi-2223	1st cool-down	0	–0,09	–0,14	–0,17	–0,20	–0,20	–0,20	
Composite tape[a]	2nd cool-down	0	–0,11	–0,18	–0,23	–0,27	–0,27	–0,27	
Silver[b]		0	–0,135	–0,221	–0,301	–0,360	–0,374	–0,375	–0,375
OFHC Copper Annealed[c]		0	–0,118	–0,18	–0,252	–0,288	–0,295	–0,295	
G10, warp[d]		0	–0,09	–0,13	–0,175	–0,205	–0,215	–0,220	–0,225
G10, normal[d]		0	–0,28	–0,428	–0,54	–0,62	–0,64	–0,65	–0,655
Stainless steel AISI SUS316[c]		0	–0,111	–0,173	–0,23	–0,262	–0,265	–0,265	–0,265
Stainless steel AISI SUS304[c]		0	–0,11	–0,172	–0,23	–0,261	–0,264	–0,264	–0,264

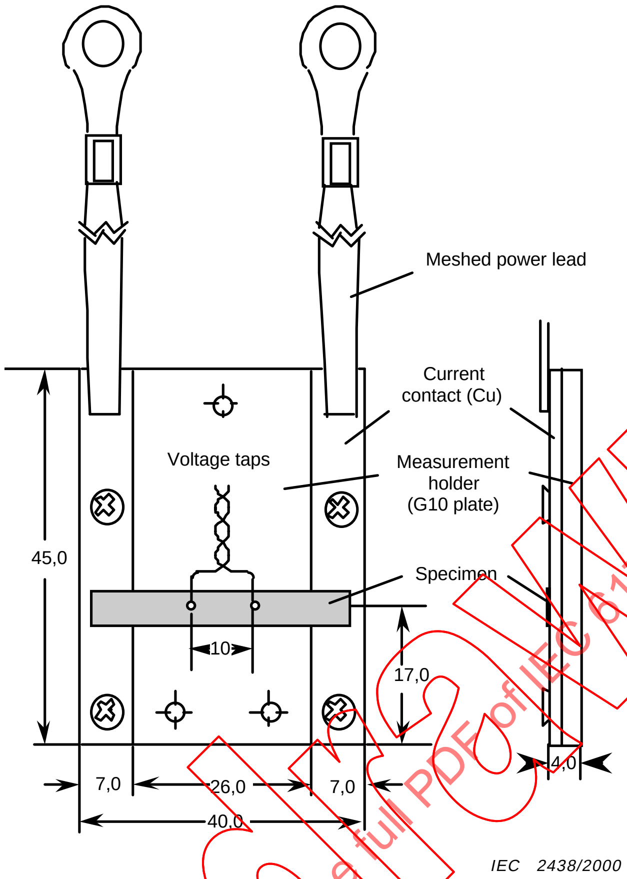
NOTE Thermal expansions are referred to zero at 273 K.

[a] O. Yamada, *et al.*, Cryogenics, vol. 38, No. 4 (1998) 397.

[b] Properties of Materials at Low Temperature (Phase 1), edited by V.J. Johnson, Pergamon Press (1961).

[c] Handbook on Materials for Superconducting Machinery, NBS (1974, 1976).

[d] A.F. Clark, *et al.*, IEEE Trans. on Magnetics, MAG-17 (1981) 2 316.



Dimensions in millimetres

Figure A.1 – Illustration of a measurement configuration for a short specimen of a few hundred A class conductors

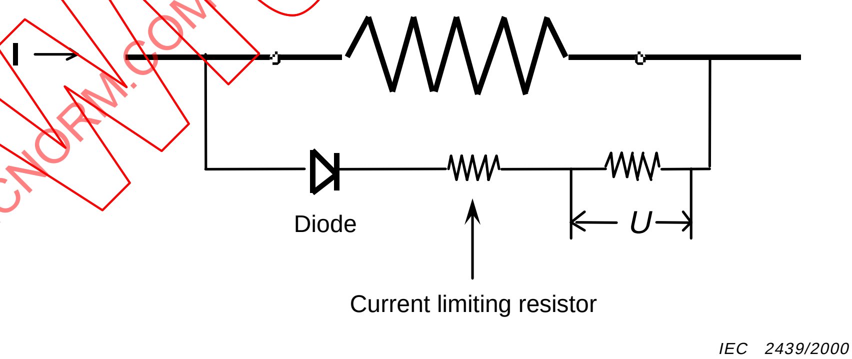


Figure A.2 – Illustration of superconductor simulator circuit

Annex B
(informative)

Magnetic hysteresis of the critical current of high-temperature oxide superconductors

B.1 Magnetic hysteresis

The measured critical current (I_c) of a high-temperature oxide superconductor can have a significant dependence on the history of the temperature, current, and applied magnetic-field strength and angle. As for magnetic-field strength, I_c at a given magnetic field of some multifilamentary Bi-2223 conductors can be as much as 100 % higher when they are measured with monotonically decreasing fields (from a higher field) compared to monotonically increasing fields. The I_c measured at zero magnetic field after a magnetic field sweep, can be lower than the initial I_c measured at zero field by as much as 40 %. The I_c hysteresis of some multifilamentary Bi-2212 conductors can be much less. It can be as low as 5 % to 10 % at low magnetic fields and as low as 2 % at high magnetic fields. This magnetic hysteresis of the I_c is due to weak links in a high-temperature oxide superconductor and can be removed by heating the superconductor above its critical temperature (T_c).

B.2 Sequence of measurement conditions

The sequence of conditions in a given application determines the appropriate sequence during the measurements. For the example of a tape conductor near the mid-plane of a simple solenoid magnet, the sequence of conditions would be: the conductor is cooled to the operating temperature and then the current and the magnetic field (parallel to the face of the tape) are ramped up together along the load-line of the magnet until the operating current or I_c is reached.

In a typical I_c measurement where the hysteresis with sample current can be regarded as small, this is simplified and the practice may be: the sample current and the magnetic field are ramped independently and the I_c is measured at a number of fixed and monotonically increasing magnetic fields.

The possible improvement in the I_c by first exposing the sample to higher magnetic fields is not a relevant sequence unless this is somehow to be accomplished in the application. Thus, in general, the relevant sequence of parameters is:

a) the specimen is cooled in zero field, from a temperature above T_c down to the measuring temperature;

b) the desired field angle with respect to the conductor cross-section is fixed;

c) the I_c can be measured at various, monotonically increasing magnetic fields.

If I_c data at other field angles is needed, the specimen must be heated to a temperature above T_c and the above sequence repeated.

B.3 Reduction of magnetic hysteresis

The effects of magnetic hysteresis can be reduced by ramping the magnet to a lower or zero field and then back up to the test field. Using this technique, acceptably low hysteresis can be demonstrated on Bi-2223 conductors for the higher magnetic fields (for example 4 T at 4,2 K). If this can be demonstrated on a given conductor, then the step of warming and cooling in zero field can be omitted.

The effect of hysteresis on I_c may depend on many factors such as: material processing, magnetic field strength, field angle, temperature, criteria, and extent of field sweep. As these materials evolve, the magnitude of the hysteresis effects may be reduced.

B.4 Magnetic field angle dependence

Similar magnetic hysteresis of the I_c has been observed in magnetic-field angle dependence measurements on tape specimens. The I_c at a given magnetic-field angle of some multifilamentary Bi-2223 conductors can be as much as 50 % higher when they are measured with an angle sweep direction that results in a decreasing normal magnetic-field component (field perpendicular to the face of the tape) compared to an angle sweep direction that results in an increasing normal magnetic-field component. As with field sweeps, angle sweeps result in fairly reproducible hysteresis loops, except the first point (the point that was arrived at with the relevant sequence of conditions) is not repeated. Comparisons of angle dependence measurements at fixed angles to angle sweeps shows these data are related; however, if significant hysteresis exists, the data obtained from angle sweeps will be significantly different for some angles. These differences can be as large as 20 %.