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INTERNATIONAL STANDARD

NORME INTERNATIONALE

Superconductivity –
Part 14: Superconducting power devices – General requirements for characteristic tests of current leads designed for powering superconducting devices

Supraconductivité –
Partie 14 : Dispositifs supraconducteurs de puissance – Exigences générales pour les essais de caractéristiques d'amenées de courant conçues pour alimenter des dispositifs supraconducteurs

IEC 61788-14:2010-06(en-fr)

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SUPERCONDUCTIVITY –

Part 14: Superconducting power devices – General requirements for characteristic tests of current leads designed for powering superconducting devices

FOREWORD

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International Standard IEC 61788-14 has been prepared by IEC technical committee 90: Superconductivity.

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

FDIS	Report on voting
90/244/FDIS	90/250/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.

The French version of this standard has not been voted upon.

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

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

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

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- withdrawn,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

INTRODUCTION

Current leads are indispensable components of superconducting devices in practical uses such as MRI diagnostic equipment, NMR spectrometers, single crystal growth devices, SMES, particle accelerators such as Tevatron, HERA, RHIC and LHC, experimental test instruments for nuclear fusion reactors, such as ToreSupra, TRIAM, LHD, EAST, KSTAR, W7-X, JT-60SA and ITER, etc., and of advanced superconducting devices in the near future in practical uses such as magnetic levitated trains, superconducting fault current limiters, superconducting transformers, etc.

The major functions of current leads are to power high currents into superconducting devices and to minimize the overall heat load, including heat leakage from room temperature to cryogenic temperature and Joule heating through current leads. For this purpose, current leads are dramatically effective for lowering the overall heat load to use the high temperature superconducting component as a part of the current leads.

On the other hand, the current lead technologies applied to superconducting devices depend on each application, as well as on the manufacturer's experience and accumulated know-how. Due to their use as component parts, it is difficult to judge the compatibility, flexibility between devices, convenience, overall economical efficiency, etc of current leads. This may impede progress in the growth and development of superconducting equipment technology and its application to commercial activities, which is a cause for concern.

Consequently, it is judged industrially effective to clarify the definition of current leads to be applied to superconducting devices and to standardize the common characteristic test methods in a series of general rules.

SUPERCONDUCTIVITY –

Part 14: Superconducting power devices – General requirements for characteristic tests of current leads designed for powering superconducting devices

1 Scope

This part of IEC 61788 provides general requirements for characteristic tests of conventional as well as superconducting current leads to be used for powering superconducting equipment.

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

IEC 60071-1, *Insulation coordination – Part 1: Definitions, principles and rules*

IEC 60137, *Insulated bushings for alternating voltages above 1 000 V*

3 Terms and definitions

For the purposes of this document, the terms and definitions contained in IEC 60050-815:2000 as well as the following terms and definitions apply:

3.1
current lead
power lead
conductor to introduce electric current into a device with an insulation and a cooling channel especially when leading from room temperature to cryogenic temperature

[IEV 815-06-47]

3.2
normal conducting current lead
conventional current lead
current lead made only of a normal conducting section

3.3
superconducting current lead
current lead containing a superconducting section

NOTE A superconducting current lead consists of a normal conducting section from room temperature to intermediate temperature and a superconducting section from intermediate temperature to cryogenic temperature. In this standard, the superconducting section is mostly made by a high temperature superconductor (HTS).

3.4
non-gas cooled type current lead
current lead cooled by conduction cooling method

3.5
gas-cooled type current lead
current lead cooled by a cooling gas

NOTE In some cases, the gas cooling is made between cooling via gas flow inside the leads and (additional) convection cooling on the outside surface.

3.6
self-cooled current lead
vapour enthalpy cooled current lead
current lead capably cooled by an evaporated gas generated by heat load from current leads into cryogen

3.7
heat leakage
non-current heat leakage
heat conducted from higher temperature portion into lower temperature portion of the current lead at zero current operation without any Joule heating

3.8
heat load
total heat induced into a cryogenic system through the current leads under current-carrying operation

3.9
rated current heat load
heat load at a rated current operation

4 Principles

The powering of superconducting equipment is made via components that provide the electrical link between the room temperature environment and the cryogenic temperature of the powered equipment. These components are called current leads. Since they operate in a gradient of temperature and they transport current into the cryogenic environment, they are one of the major sources of a heat leakage into the cryostat.

The current leads can be classified into two types:

– normal conducting current leads, made entirely from normal conducting section. These are usually joined at their cold end to a superconducting (SC) bus or link leading to the device being powered;
– high temperature superconducting (HTS) current leads, which incorporate a section of HTS material. A normal conducting section is necessary to conduct the current from room temperature to the warm end of the HTS section. The latter must be maintained at a sufficiently low temperature to ensure that it remains superconducting for the maximum rated current of the lead. The cold end of the HTS section is usually joined to the device by a SC bus.

Depending on the cooling method, the leads can be either non-gas-cooled or gas-cooled. Both types of cooling methods can be used if the lead is subdivided into two, hydraulically separated, sections. If the device being powered uses low temperature superconducting (LTS) material, the link to the lead is usually via LTS cables or wires.

Optimized, self-cooled normal conducting current leads conduct into the helium bath 1,1 W/kA [1][1)] to 1,2 W/kA [2]. This value can be reduced substantially by using HTS material. HTS current

1) Figures in square brackets refer to the Bibliography.

leads have been extensively studied, designed and tested, and are already being integrated into large-scale systems [3] [4].

The design of a current lead is uniquely linked to the system within which it has to operate. The choice of materials, the cooling method, the geometry, the electrical characteristics and the admissible cryogenic consumptions are strongly influenced by boundary conditions imposed by the whole system. System requirements are electrical, cryogenic, and mechanical, and include the following:

– maximum operating current, operation mode, current ramp rate, insulation voltage, circuit time constant, ambient magnetic fields;
– cryogen availability, cryogen inlet/outlet temperature and pressure, admissible heat loads, time duration when the lead shall operate safely in case of failure of cryogen supply;
– the volume available for integration, including mechanical support, vacuum insulation, and connection to the hydraulic and electrical interfaces.

NOTE 1 The heat leakage for self-cooled current leads should make use of 1,2 W/kA in the case of large current capacities.

NOTE 2 Typical current leads based on these principles are shown in Annex B.

5 Characteristic test items

The following clauses describe the qualification tests that should be performed on a current lead at both room and cryogenic temperatures in order to verify its mechanical, electrical and thermal performance. It is assumed that the design of the current lead has been carried out in consideration of general versatility. Before application to an actual system, it is also necessary to do the optimization of the current lead according to the constraints imposed by each system. The characteristic test items shown in Table 1 should enable the user to verify if the current lead meets the specified requirements, and to judge if the test items meet the execution stage of the current lead. It is the responsibility of the user of this standard to select the appropriate tests according to Table 1 considering the boundary conditions of the current leads.

Table 1 – Characteristic test items and test execution stages for current leads

	Characteristic test category	Test items	Characteristic test execution stage		
			R&D[a]	Catalogue[b]	Receive[c]
1	Mechanical characteristics	Structure inspection		Yes	Yes
		Stress/strain effect test	Yes		
2	Thermal properties	Non-current heat leakage test	Yes	Yes	
		Rated current heat load test	Yes	Yes	
3	Electrical characteristics	Rated current-carrying test	Yes	Yes	
		Contact resistance test	Yes		
		High voltage test	Yes	Yes	
		Voltage drop test	Yes	Yes	
4	Hydraulic characteristics	Pressure drop test with rated gas flow	Yes	Yes	
		Leak tightness test	Yes		
5	Safety margin characteristics	Cryogen failure test	Yes	Yes	
		Quench test	Yes		
		Maximum pressure test	Yes	Yes	

NOTE 4 Characteristic test items and methods for the components of HTS section are shown in Annex D.

[a] "R&D" means the test stage for basic research or trial productions of current lead systems.

[b] "Catalogue" means the test stage for performed R&D or mass production of the current leads.

[c] "Receive" means the test stage after installation of the current lead system in the site.

6 Characteristic test methods

The test methods listed here are recommendations. The user may also select other test methods if required by specific applications or boundary conditions.

6.1 Structure inspection

6.1.1 Purpose

This test shall inspect dimensions, applicable materials, structure, structural state and so on as well as the thermal insulation property and leak tightness of the container in the target system.

6.1.2 Methods

The structure inspection test at room temperature shall inspect dimensions, applicable materials, structure, structural state and so on.

The structure inspection test at low temperature shall inspect visually the state of frost forming on the surface of a cryostat filled with cryogen or connected to a refrigerator. As for cryostats with the vacuum thermal insulating layer, it shall be confirmed that there is no malfunction in the layer such as tears and/or collapsing.

6.1.3 Results

Test results shall be collated with the specifications and fully reported.

6.2 Stress/strain effect test

6.2.1 Purpose

This test shall confirm the mechanical stress/strain effect on the current leads at room temperature and low temperatures.

6.2.2 Methods

A mechanical stress/strain level at room temperature and low temperatures in the target system shall be simulated, and mechanical stress/strain is loaded up to the maximum level below the elastic limit of the superconductor.

NOTE 1 The maximum load should be defined depending on the safety margin, and is typically 1,1 times the specification level.

NOTE 2 The test should be done repeatedly a specified number of times by distinguishing the condition between electromagnetic loading and thermal loading.

NOTE 3 Special notice should be taken of internal stress/strain appearing due to the cooling of the current leads from room temperature to operating conditions.

6.2.3 Results

Test results shall be collated with the specifications and fully reported.

6.3 Thermal property test

6.3.1 Non-current heat leakage test

6.3.1.1 Purpose

This test shall measure the non-current heat leakage, which is observed at zero current without any Joule heating, associated with the heat conduction from the room-temperature end to the intermediate-temperature portion, from the intermediate-temperature portion to the low-temperature end or from the room-temperature end to the low-temperature end of current leads.

6.3.1.2 Methods

The heat leakage shall be measured by the evaporation method of liquid cryogen, the enthalpy change method of forced flow cryogenic gas or the thermal conduction method using a cryocooler, depending on the cooling condition of the testing current leads.

a) Evaporation method

   The current leads are installed in a special cryostat for the heat leakage test with known values of background heat leakage into the measurement region. In the cryostat the cold ends of the current leads are cooled with an appropriate coolant such as liquid helium and/or liquid nitrogen. The mass flow rate of evaporated coolant is measured at the outlet of the cryostat. The heat leakage through the current leads is evaluated by analyzing an increment in the mass flow rate of evaporated coolant by installing the current leads. Corresponding measurements should be carried out in the case of the intermediate-temperature portion.

b) Enthalpy change method

   The current leads are installed in a cryostat with known values of background heat leakage into the measurement region. The temperature and mass flow controlled forced flow cryogenic gases such as supercritical helium are supplied to the cooling portions of the current leads. The heat leakage through the current leads is evaluated by the enthalpy changes of cryogenic gases between inlet and outlet of the current leads.

c) Thermal conduction method

The current leads are installed in a cryostat with known values of background heat leakage into the measurement region. The cooling portions of the current leads are thermally connected to the cold heads of the cryocooler. The heat leakage through the current leads is evaluated by the increment of heat loads to the cold heads of the cryocooler.

NOTE 1 In the evaporation method, a part of evaporated coolant remains in the cryostat as a low-temperature gas. Because the density of a low-temperature gas is large, it is necessary to correct the amount of the evaporated coolant when the mass flow rate is measured at the outlet of the cryostat.

NOTE 2 In R&D, the value of the heat leakage through the current lead is estimated from the numerical solution of the energy balance equation along the conductor of the current lead. Temperatures of cold and warm ends are taken to be boundary values of the energy balance equation. The form of the energy balance equation depends on the structure of the current leads. In the case of the gas-cooled normal conducting current leads, the energy balance equation may consist of such terms as heat conduction, ohmic heat generation and heat exchange with cooling gas.

6.3.1.3 Results

Test results shall be collated with the specifications and fully reported.

6.3.2 Rated current heat load test

6.3.2.1 Purpose

This test shall measure the amount of heat load at the rated current.

6.3.2.2 Methods

The methods shall be pursuant to those of the non-current heat leakage test without current (6.3.1.2).

6.3.2.3 Results

Test results shall be collated with the specifications and fully reported.

6.4 Rated current-carrying test

6.4.1 Purpose

This test shall confirm performances of the current leads at the rated current under the normal operation conditions.

6.4.2 Methods

To compare the performances of the current leads to the design values, the temperature profile shall be measured. The measuring points of temperature shall be at least the three positions of the room-temperature end, the intermediate-temperature portion and the low-temperature end. It shall be noticed that the temperature of the room-temperature end is affected by boundary conditions such as size, cooling condition of the bus bar, and so on.

The temperature rise shall be measured usually by the thermometer method or the resistance method.

Prior to the test, all cooling conditions of the refrigerator, the cryogen level or others shall be confirmed.

The current of the leads shall be maintained at the rated value until the cooling condition settles down in the steady state.

A typical example of temperature profile during the rated current-carrying test is shown in Clause C.1 of Annex C.

6.4.3 Results

Test results shall be collated with the specifications and fully reported.

6.5 Contact resistance test

6.5.1 Purpose

This test shall measure the contact resistance between HTS parts and normal conducting parts at intermediate-temperature portions. The contact resistance between HTS parts and LTS parts at low-temperature ends shall be measured, if it is required for the current leads.

6.5.2 Methods

The measurement of the total contact resistance, including the target contact section, shall be performed by the four-terminal method. The test results shall be corrected for the additional resistances due to other sections, except for that of the target contact.

NOTE For a current lead of small capacity less than a few kA, the influence of the two-dimensional current distribution on the contact resistance can be disregarded. However, the measurement and the correction by analysis or simulation considering the current distribution at the target joint shall be necessary for the current lead of the large capacity. Therefore, it is very difficult to get accurate value of the contact resistance. Even in this case, it is necessary to confirm the contact resistance is at least below the tolerance value by correcting the measurement with analysis or simulation considering the two-dimensional current distribution at the target joint.

6.5.3 Results

Test results shall be collated with the specifications and fully reported.

6.6 Voltage drop test

6.6.1 Purpose

This test shall confirm that the voltage drop of the current leads under the rated current is as expected from design calculations.

6.6.2 Methods

The cooling conditions shall conform to those of the rated current-carrying test.

The voltage drop shall be measured by the voltage taps between the room-temperature end and the low-temperature end.

6.6.3 Results

Test results shall be collated with the specifications and fully reported.

6.7 High voltage test

6.7.1 Purpose

This test shall confirm that there is no abnormality in the voltage drop property having an influence on the insulation performance of current leads.

6.7.2 Methods

Prior to the test, make sure that there is no problem associated with the insulation performance of the current leads, by using an insulation-resistance tester. Apply a given test voltage to current leads for more than one consecutive minute. The test voltage applied has to be in accordance with the requirements of the system in which the current lead shall be used.

For current leads for alternating-current equipment, the test shall be pursuant to the withstand voltage specification of the target equipment. For this, IEC 60071-1 and IEC 60137 shall be applied.

NOTE The Paschen tightness may be required by the system that demands high reliability. The Paschen tightness means that in case of a vacuum leak of the cryostat, the system must withstand the applied voltage even at the so called Paschen minimum that occurs at the pressure range of 0,1 kPa to 1 kPa. (A typical dependence of the breakdown voltage on pressure is shown in Clause C.2). To carry out this test, the current lead has to be installed in a vacuum vessel which is evacuated. After applying a required test voltage, the pressure in the vessel is slowly increased until normal pressure. During the whole process, the leak current between the current lead and ground potential is continuously monitored.

6.7.3 Results

Test results shall be collated with the specifications and fully reported.

6.8 Pressure drop test

6.8.1 Purpose

This test shall measure the pressure drop in the current lead at the rated pressure and the rated mass flow of cryogenic gas.

6.8.2 Methods

Pressure differences of the cryogenic gas between inlet and outlet of the current lead shall measure by a pressure gauge. The absolute pressure of inlet and/or outlet of the current lead should be specified.

6.8.3 Results

Test results shall be collated with the specifications and fully reported.

6.9 Leak tightness test

6.9.1 Purpose

This test shall confirm the adaptability on leak tightness between current leads and superconducting equipment.

6.9.2 Methods

For the gas-cooled type current leads, install them in a cryostat with the air-side open end sealed and confirm the leak tightness by a leak detector.

For the non-gas-cooled type current leads, this test shall be carried out under installation of the current leads into the cryostat, if requested.

6.9.3 Results

Test results shall be collated with each specification based on the type of the current leads and fully reported.

NOTE Test results shall be collated with each specification of the gas cooled type current leads or the non-gas cooled type current leads depending on different design conditions of the withstand hydraulic pressure and the leakage tightness based on the operation condition, the environmental condition etc. of the superconducting devices.