METHODS AND APPARATUSES FOR STUDY OF CRITICAL CHARACTERISTICS OF HIGH-CURRENT SUPERCONDUCTORS

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Abstract

The complex of measuring devices has been created in IHEP to study the characteristics of low-temperature superconductors for currents up to 20 kA. The current-voltage characteristics of short superconducting (SC) cable samples, based on multifilament Nb-Ti alloy superconductors, were measured. The critical currents, depending on a temperature and a magnetic field up to 8 T, were measured,. The equipment was designed for measuring the minimum quenching energy (MQE) of SC sample in the normal state. It allows study the stability of the material to a short-term heat production on a separate piece of wire that is a part of the cable. The parameters of different designs of SC transformers for obtaining currents above 10 kA in the samples of partially stabilized SC cable coils of dipole and quadrupole magnets of accelerator storage complexes are given. The capabilities and limitations of different equipment options are compared.

INTRODUCTION

Superconducting magnets are widely used in a physical experiment, in particular, they are used in the magnetic structure of ultrahigh-energy accelerators [1]. For dipoles and quadrupoles of ring accelerators and colliders, the operating conditions of the current-carrying element of coils, based on the Nb-Ti alloy, is a current of 5-13 kA under the induction of the external magnetic field up to 8 T and at the temperature of 4.2 K or lower [2].

The main task in developing and optimizing the parameters of the SC cable is to obtain the maximum value of the operating current (and, correspondingly, the maximum permissible current density), while reducing the level of dynamic losses. For the dipole magnets of the SIS-300 accelerator, which is the last stage of the FAIR, the IHEP developed an SC-cable with a working current of 6 kA in the external magnetic field of 6 T and a temperature of 4.2 K, the ratio of copper/superconductor in the wires of the cable is 1.4 [3].

It is necessary to investigate the stability of the SC cable to thermal disturbances, arising in the magnet during its operation, in the SC cable with partial stabilization, along with the current-voltage characteristic I-V, $I_C(B, T)$. The criterion of stability is MQE.

When the current-carrying capacity of a 10 kA cable is reached, the conventional method of the introducing current from an external power supply becomes impractical because of arising a large heat in the low-temperature zone in the current leads. The induction method of current injection, using an SC transformer is used in the SC sample to reduce the losses of liquid helium and to achieve high current values. Further, options for the designs of transformers will be considered.

METHODS AND APPARATUSES FOR RESEARCH OF CRITICAL CURRENTS

The equipment, based on the SC-transformer, has been created, which makes it possible to carry out a measurement of the current-voltage characteristic of a short sample of a SC cable up to a current of 20 kA at the liquid-helium temperature (4.2 K). The coils of the transformer are extended in length and are produced in the shape of a racetrack, which allows one to insert a rod into the aperture with a diameter of 40 mm. A magnetic field up to the maximum of 8 T is produced by a SC solenoid [4].

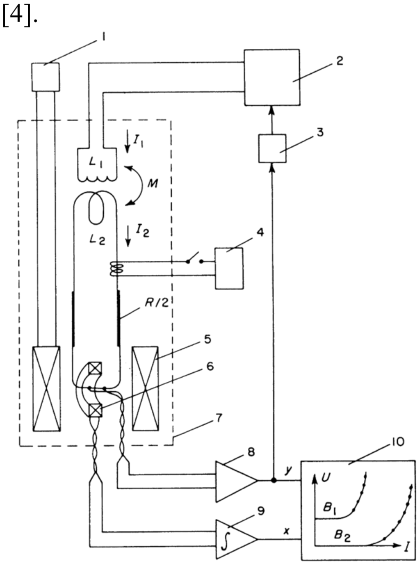

Figure 1: Scheme of the apparatus. 1 – solenoid power supply; 2- primary power supply; 3 – feed-back voltage level selection; 4 – heater power supply; 5 – solenoid; 6 – Rogowski coil; 7 – cryostat; 8 – sample voltage amplifier; - integrator; 10 – *x-y* plotter.

The automated system with a digital comparison scheme was developed by the criterion of the chosen voltage [5] for continuous measurement of the critical current dependence on the magnetic field $I_C(B)$ of SC wire samples. The use of this equipment in combination with the SC transformer allowed recording the I-V characteristic, starting from the level of 0.1 μV on the measuring section of the SC cable of various designs [6]. The scheme of the apparatus is presented in Fig. 1, general view of the device is presented in Fig. 2.

Such measurements were followed by a rapid input of current into the primary coil of the SC transformer until

ISBN 978-3-95450-197-7

the specified voltage level appeared on the measuring section of the short sample, which allows one to reduce the influence of the current decay on the junctions. The speed of the current input to the primary coil was reduced upon reaching a predetermined voltage level in the measuring section of the sample, which made it possible to study in detail the I-V characteristic, using a sensitive, but inertial voltage amplifier.

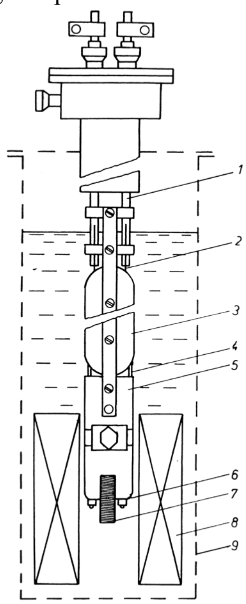

Figure 2: The cryostat insert in the cryostat. 1 - current lead; 2 – primary conductor; 3 - transformer; 4 - secondary conductor; 5 - sample holder; 6 – sample; 7 – Rogowski coil; 8 – solenoid; 9 – cryostat.

The removable rod is easily inserted and removed from the solenoid, which is in the cryostat with liquid helium.

An installation for investigate the dependence of $I_C(B, T)$ with an independent change in two basic parameters (magnetic field and temperature) was created [7]. This installation consists of a SC transformer, having thermally isolated windings. Figure 3 shows the design of a device that contains a cryostat, where the solenoid and the primary winding of the transformer are permanently located. The secondary winding of the transformer is located on the replaceable rod together with the studied sample. This design allows one to get rid of heat influx to the sample by current leads and reduce the mass of the object in the temperature control zone. The sample is replaced without warming the cryostat.

The cooling of a short sample is carried out by a gas flow with a specified temperature level, which can vary up to 21 K. Liquid helium enters to the heat exchanger, where it evaporates and is heated to the desired temperature by electric heaters.

When the current was introduced into the sample, the current-voltage characteristic and the temperature dependence of the sample were measured simultaneously. The characteristics were recorded prior to the transition of the SC sample to the normal state, which was accompanied by an increase its temperature to 10-20 K by fast (less than 1 s) attenuation of the secondary circuit current, which protected the sample from destruction.

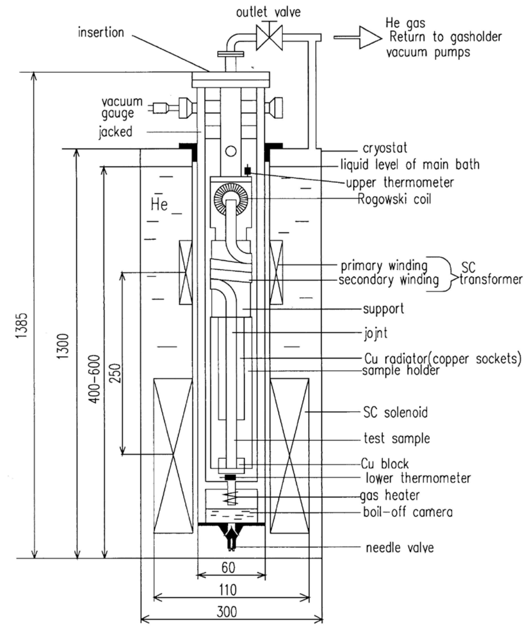

Figure 3: General view of the installation.

The semiconductor resistance thermometers is used to measure the temperature. The calibration of the temperature sensor is given by the manufacturer with a resolution of 10 mK. The magnetic field was measured by a cryogenic Hall sensor, located above the SC sample. The reproducibility of the individual values of $I_C(B, T)$ in the series of measurements at B = const was 1 - 2%.

This equipment measures the $I_C(B, T)$ dependence of short samples of a cable of dipole SC magnets at transport current values, corresponding to the transition of magnets to the normal state [8]. The obtained data made it possible to optimize the design of the SC magnet, and to predict its characteristics in the circulating cooling regime.

EQUIPMENT FOR MEASURING MQE

An installation, containing a SC transformer, was created to measure MQE at operating current up to 15 kA and a magnetic field up to 6.5 T. The design of the device, described above, is based on the principle [8].

The cable MQE is determined by a pulsed supply of heat to one wire of the cable (duration of about 50 μs). SC samples were transferred to the normal state by means of point heaters, located on the cable surface. The characteristics of the cable from 19 wires with a diameter of 0.85 mm, having different surface coatings of Ni, Cr, oxide were studied [9].

The Rutherford-type SC cable with a spacer between its layers has been developed for SC coils of magnets of the SIS300 accelerator [10]. A source of an external magnetic field with a large region of a homogeneous field is needed to investigate the MQE of this cable. An external magnetic field of up to 6 T was produced by a SC dipole.

ISBN 978-3-95450-197-7

Figure 4 schematically shows the general view and dimensions of the main elements of the installation. It consists of a SC dipole and a replaceable rod with a transformer. The critical current of the secondary SC loop was 18 kA. The single junction in the secondary circuit is soft-soldered at a length of 75 mm and provides a constant decay time of the secondary circuit current above 100 seconds. The details of the preparation of the SC sample and the main results of the measurements are given in [11].

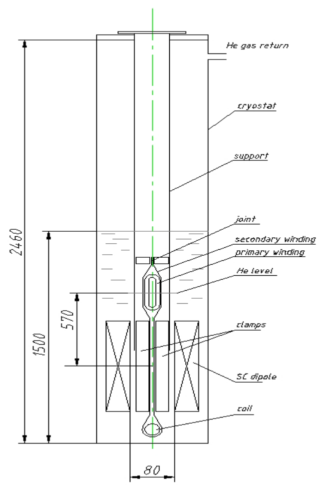

Figure 4: General view of the installation and the geometric dimensions of the main elements.

The main parameters of the SC transformers are given in Table 1. Here N_1 and N_2 are the number of turns of the primary and secondary windings of the transformer; L_1 and L_2 are the inductances of the primary winding and the secondary circuit; M is the mutual inductance between the primary and secondary windings of the transformer; I_{1max} and I_{2max} are the maximal currents of the windings; I_2/I_1 is the current transformation ratio; B_{max} is the maximal magnetic field in the studied sample.

Table 1: Basic Parameters of the SC Transformers

Parameter	N 1	N 2	N 3	N 4	N 5
N_1	360	320	480	960	260
NbTi wire, mm	0.5	0.5	0.7	0.5	0.85
I_{1max} [A]	180	184	314	100	220
L_1 [mH]	23.3	19.3	13.5	45.0	8.0
N_2	2	1	3	3	1
M [μH]	130	60	30	60	33
L_2 [μH]	1.3	0.5	0.6	0.6	0.4
I_{2max} [kA]	11.6	21.2	13.9	15.3	18.0
I_2/I_1	86.7	120.0	49.0	75.0	84.0
B_{max} [T]	8.0	8.0	5.8	6.75	6.0
references	[4]	[6]	[7]	[9]	[11]

In the designs N 1 and N 2, the windings have the shape of a racetrack, and the difference lies in the material of the winding of the secondary circuit, the transformer N 5 also has windings of the racetrack type. The windings of N 3 and N 4 transformers are solenoids.

The sample current is measured by an electronic integrator that is connected to a toroid. A high-speed amplifier was used to measure the voltage in the measuring section of the sample. An electric heater was activated to eliminate the residual currents in the secondary SC circuit before the procedure for measuring the characteristics.

CONCLUSIONS

New methods and different designs for devices, containing the SC transformers for feeding studied SC samples with high currents up to 20 kA have been developed. This approach give a possibility to investigate the behavior of samples of composite SC material. The use of the SC transformer guarantees the obtaining of high current values and at the same time provides the protection of the sample from burnout during a transition to the normal state.

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ISBN 978-3-95450-197-7