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CRYOGENIC TEST OF HIGH TEMPERATURE SUPERCONDUCTING CURRENT LEADS AT ENEA

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ABSTRACT

The LHC (Large Hadron Collider), the accelerator being constructed on the CERN site, involves the operation of more than 8000 superconducting magnets of various current ratings. Essential elements for the powering of these magnets are the HTS current leads. These devices provide the electrical link between the warm cables from/to the power converter and the low temperature superconducting bus bars bringing the current from/to the cryo-magnets. Thus they operate in a temperature range between room temperature and liquid helium temperature. The operation of the LHC will require more than 1000 HTS current leads operating at currents ranging from 600A to 13000A. Cryogenic tests of the series of 13000A and 6000A HTS current leads are made at ENEA in the framework of a CERN-ENEA collaboration.

This report gives an overview of the experimental set-up built in ENEA. The set-up was designed following the typical criterion of a scientific experiment but it was dimensioned to satisfy the schedule of an industrial scale activity, having in mind the large number of components to be tested in a period of less than two years. The related data acquisition system is also described, together with the results of the tests on the current leads.

KEYWORDS: Cryogenics, Current leads, HTS devices
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INTRODUCTION

The Large Hadron Collider (LHC) is a particle accelerator and storage ring, which will probe deeper into matter than ever before. Due to begin service in 2007, it will collide beams of protons with a centre-of-mass energy of 14TeV. Beams of lead ions will also be accelerated, to interact with a collision energy of more than 1000TeV. The LHC requires very strong magnetic fields generated by about 8000 superconducting (SC) magnets and several hundreds of normal conducting magnets, working at different current ratings. Crucial elements for LHC operation are therefore the current leads, more than 3000 in total, which will feed the SC magnets [1]. For the leads rated at currents ranging from 600A to 13000A, more than 1000 in total, CERN decided to use High Temperature Superconducting (HTS) technology [1]. The design of these leads has been made by CERN [2], where 600A, 6000A and 13000A prototypes were built and tested in nominal operating conditions and a pre-series of 156 units was assembled.

ENEA has been entrusted, in September 2004, with the cryogenic tests of the complete series of 6000A and 13000A LHC HTS current leads, consisting of 333 units [3]. In addition, ENEA tested a pre-series of 14 assemblies of four HTS current leads rated at 600A. In the context of electrical characterization of series of cryogenic devices, ENEA had already collaborated with CERN for the testing campaign, successfully completed at the end of 2004, of the 1400 by-pass diode stacks used for the LHC main dipole and quadrupole magnets quench protection [4].

This paper outlines the dedicated experimental facility built at ENEA for the HTS current leads test, describes the procedures adopted in order to satisfy CERN technical requirements [3], and reports on the performance results of the more than 100 current leads tested up to now.

CURRENT LEAD CHARACTERISTICS

The design of the HTS current leads is described in detail elsewhere [1,2,3]. Their operation requires helium gas at about 20K and 0.13MPa, for the cooling of the resistive part, and liquid helium covering the bottom end of the HTS element and the Low Temperature Superconducting (LTS) wires termination. The top part of the HTS element operates at about 50K.

The current leads rated for 6000A and 13000A are supplied as single units. They are tested in pairs, electrically connected at the free end of the LTS wires. The current leads rated for 600A are supplied assembled on a single flange in a group of four. A common manifold distributes the 20K helium gas to the four units. The four leads are connected electrically in series in order to be tested in a single run.

Instrumentation is incorporated inside the lead body during the construction of the current leads. It consists of voltage taps, for the protection of both the resistive and the superconducting section of the leads, and temperature probes, for the control of the 20K helium mass flow rate and the monitoring of the temperature at the top part of the lead.

Cartridge heaters are integrated at the top part of each lead to avoid condensation in stand-by operation.

TABLE 1 summarises the total number (N_{TOT}) of HTS leads to be tested at ENEA, their corresponding nominal current (I_{nom}) and their mass and overall dimensions.

TABLE 1. Number of HTS leads to be tested and their overall dimensions

I_{nom} (A)	N_{TOT}	∅ of external envelope (m)	∅ of the insulating mounting flange (m)	Length (m)	Mass (kg)
13000	64	0.128	0.218	1.5	70
6000	269	0.08	0.218	1.5	50
600	56	0.05	0.255	1.26	40 (4 lead assembly)

TEST PROCEDURE AND EXPERIMENTAL APPARATUS

Pre-Test checks

The electrical insulation, the leak tightness of the vacuum jacket and of the 20K circuit (TABLE 2), and the integrity and continuity of the instrumentation signals inside the lead body are checked before placing the leads in the cryostat. The insulation test values and the maximum leakage current ($I_{LEAKAGE}$) admitted for each type of lead are given in TABLE 3. The insulation test of the lead is performed with warm helium gas (295±5K, 0.13MPa) in the resistive heat exchanger and in the cryostat environment. During the high voltage (HV) insulation tests, the lead instrumentation is left floating.

TABLE 2. Nominal and design pressures and leak rate for the hydraulic circuits

Hydraulic circuit	Inlet pressure (MPa)	Design pressure (MPa)	Leak rate (0.1 Pa-m^3-s^{-1})
20 K He gas	0.13 ± 0.01	0.35	$\leq 1\cdot10^{-6}$
4.5 K LHe	0.12 ± 0.01 (saturated helium bath pressure)	0.35	$\leq 1\cdot10^{-6}$
vacuum insulation of the resistive part			$\leq 1\cdot10^{-8}$

TABLE 3. Insulation test voltage of current leads (helium @ 295K ± 5 K, 0.13 MPa)

Lead current rating (A)	Insulation voltage (V)	Leakage current (μA)	Voltage Test duration (s)
600	1500	$\leq \lvert 3 \rvert$	30
6000	1300	$\leq \lvert 10 \rvert$	30
13000	3100	$\leq \lvert 20 \rvert$	120

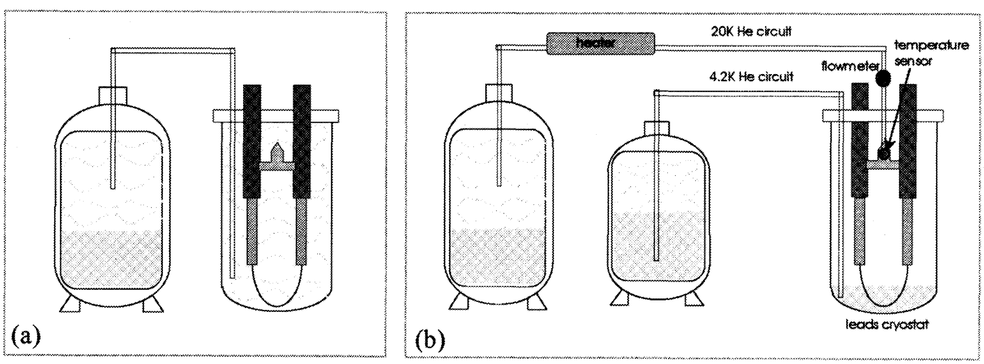

FIGURE 1. Phase (a) is performed using He vapour while during the cool down (b) the cryostat is filled with LHe.

Test procedure

During cool-down of the test cryostat, all the temperature signals inside the current lead, the inlet temperature and the mass flow rate of the helium gas cooling the resistive heat exchanger are recorded.

Two separate Dewars containing liquid helium (LHe) are used for cooling down the leads: one to transfer directly LHe for the bath, the other to obtain the 20K He gas to cool the heat exchanger (see FIGURE 1); the lance of this second Dewar doesn't dip into LHe, but in the He vapour, the temperature of which is adjusted by means of a heater placed on the circuit to be equal to 20K at the lead inlet, where it is checked by a temperature sensor. Both dewars are kept at a vapour pressure of about 0.03MPa using internal heaters.

He gas obtained by the same procedure is used to pre-cool the cryostat interior down to about 100K. The pre-cooling prevents an excessive evaporation, which would appear if LHe would be injected into the cryostat at room temperature. After this phase, LHe is introduced to form the bath in which the LTS wires of the current leads are immersed; at the same time the 20K He gas begins to flow into the heater exchangers.

The leads are powered once the temperature of the warm part of the HTS (T_{HTS}) is adjusted to the operation value (48±2K), the liquid helium level covers the last 0.05±0.01 m measured from the bottom end of the lead and the protection system is connected and operational. The resistive part of the lead and the HTS element are independently protected with voltage thresholds of respectively 100mV and 5mV.

The leads are powered up with a ramp rate of 40A/s. The constant nominal current is carried by the leads during at least 1 hour, when stable operation conditions are reached as indicated through monitoring of the HTS temperature and voltages. For the 6kA tests' only, when the measurement at nominal current has been completed, T_{HTS} is lowered to 40±2K and a constant current of 7500A is carried by the leads during one more hour. Finally, the helium flow rate inside the resistive heat exchanger is stopped and the current is made to decay exponentially with a time constant of 120s for the 13kA, 10s for the 6kA and 600A current leads.

During the test, T_{HTS} is maintained at the operational value (~50K) by fine tuning the valve regulating the mass flow rate of the 20K He gas. Once the required level in the cryostat is achieved, the LHe bath doesn't need to be refilled: its evaporation is smooth and its cooling power is sufficient for a complete cold test (up to two hours run for the 6kA leads).

While feeding the leads, the following signals are recorded versus time with a sampling rate of 1 Hz:

- current;
- helium flow rate inside the resistive heat exchanger;
- inlet temperature of the helium inside the resistive heat exchanger;
- pressure drop of the helium inside the resistive heat exchanger;
- voltage drop across the resistive heat exchanger and across the HTS unit;
- temperature of the top part the lead and of the warm end of the HTS element ;
- liquid helium level.

After the cold tests, instrumentation, electrical insulation and leak tightness are checked again at room temperature. These tests include integrity, continuity and HV tests as during pre-test checks.

Facility and data acquisition system

A dedicated area has been prepared at the ENEA Research Center of Frascati for the HTS leads testing (FIGURE 2).

The cryogenic test facility has been designed by ENEA taking into account the foreseen target of testing at least 300 leads in a period of two years. The facility comprises two vacuum insulated cryostats each able to contain either a pair of 13kA or 6kA leads or an assembly of four 600A leads connected in series. Each type of lead is mounted on a dedicated top flange, designed to suitably host the corresponding insulating mounting flange of the leads. The area is equipped with its own helium recovery line.

A switching DC power converter (5V at 16kA DC output current) powers the leads. The data acquisition system is based on National Instruments devices, while software has been developed for the scope of this work using LabVIEW® language.

TEST RESULTS

In TABLE 4 is reported the number of leads tested till now: in one year about 100 current leads have been measured at cryogenic temperatures. So far, all of them behaved perfectly following the expectation of the designer.

In FIGURE 3 the graphs of the relevant signals recorded during a test are reported. After a few minutes of current plateau, both the voltage drop across the resistive heat exchanger (U_{rhe}, left plots, right Y axis) and the temperature of the warm terminal of HTS part (T_{HTS}, left plots, left Y axis) stabilize at their operating values while keeping the 20 K helium flow rate at the nominal value for each type of lead (TABLE 5). The leads had thus reached the operation conditions and hereafter they are maintained in this situation for at least one hour, holding the same value in U_{rhe} and T_{HTS} to within ± 1mV and ± 1K respectively. Each plot shows the test results of six current leads for each type, randomly chosen among all those tested, demonstrating the outstanding reproducibility.

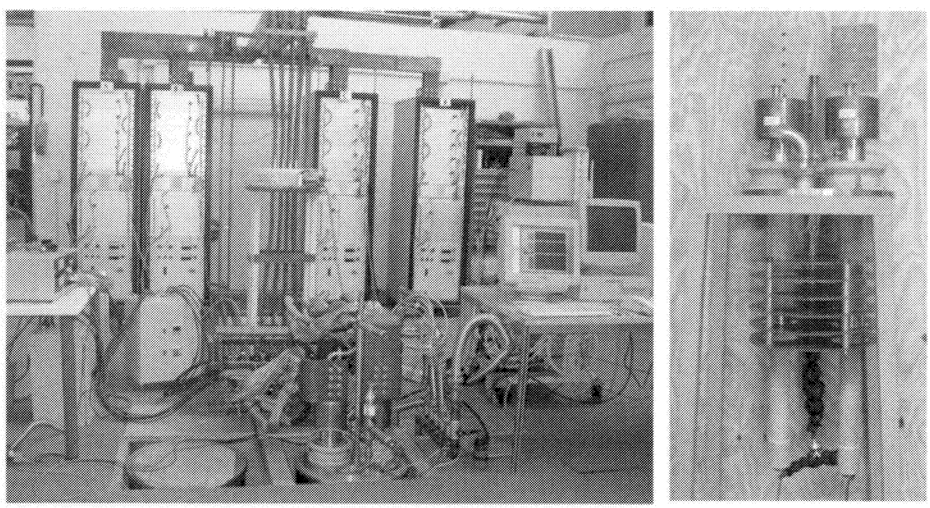

FIGURE 2. The ENEA Frascati dedicated lead test facility (a) and two 6kA mounted on the test flange (b).

TABLE 4. Number of leads tested up to now

Lead type	Units
13000 A	10
6000 A	32
600 A	56

TABLE 5. Average of the most relevant signals controlled by the operators during the leads test

	600 A	6 kA	13 kA
Mass flow rate (mg/s)	30	320	630
U_{rhe} (mV)	25	42	62
T_{HTS} (K)	33	45	50

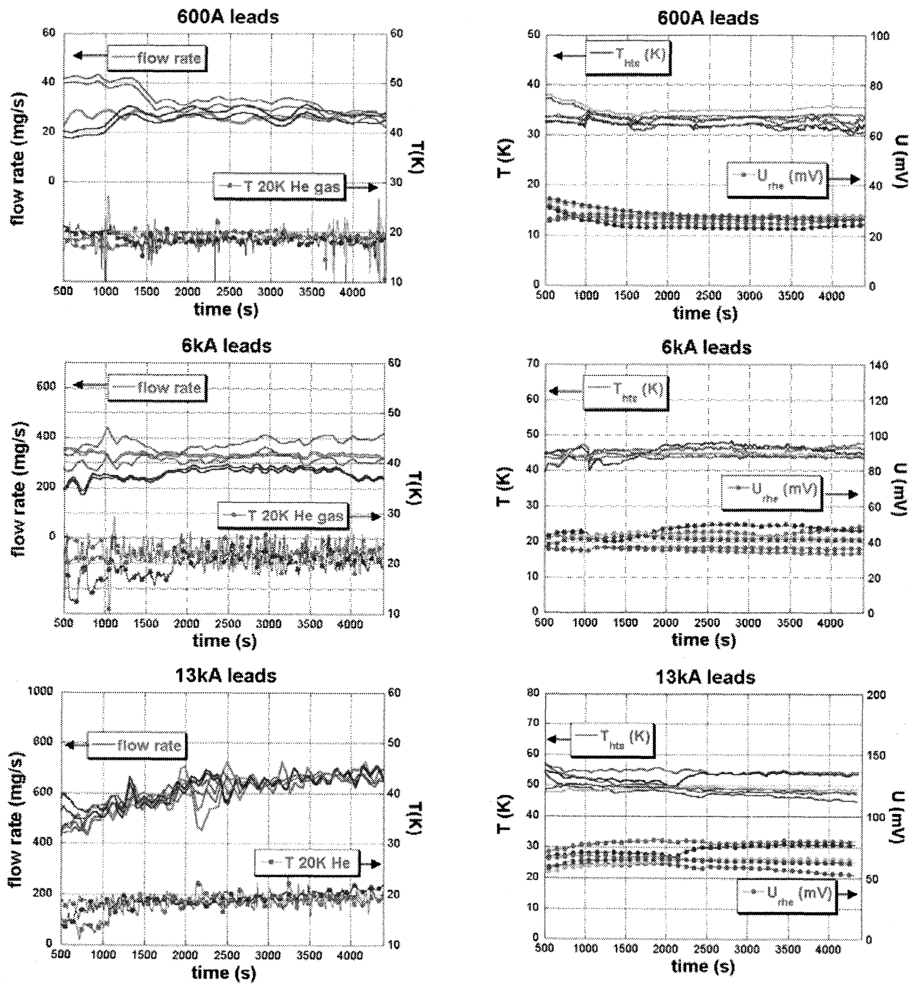

FIGURE 3. Main signals of each lead type recorded in different tests are showed together to enlighten the good repeatability of the leads behaviour as well as the facility performances.

CONCLUSIONS

To date the pre-series production, manufactured and assembled at CERN, of about 100 HTS current leads have been successfully tested. The test results show very good reproducibility of both electrical and thermal performances and fully meet the requirements of the CERN technical specification.

The ENEA dedicated facility provides high precision in the signal acquisition and subsequent interpretation, fully meeting CERN specifications.

The testing campaign is now focused on the industrial production of current leads. To satisfy the testing rate requested by CERN (cryogenic test of up to six current leads per week), ENEA has constructed two set-ups, which are operated in parallel.

The delivery of the series of HTS leads from the BINP laboratory, Russian Federation (6kA) and from CECOM, Italy (13kA) is expected to start in summer 2005.

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