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CRITICAL CURRENT TEST FACILITIES FOR LHC SUPERCONDUCTING NbTi CABLE STRANDS

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Abstract

The Rutherford-type superconducting Cu/NbTi cables of the LHC accelerator are currently mass-produced by a few industrial firms. As a part of the acceptance tests, the critical current of superconducting multifilamentary wires is systematically measured on virgin strands to qualify the wires and on extracted strands to qualify the cables. For this purpose, four test stations are in operation at CERN to measure the critical current of strands at both 4.2 K and 1.9 K in magnetic fields in the 6-11 T range. The measurement setup and procedures of these facilities are reported in this article. The quality of the critical current test is guaranteed by supervising the SPC (Statistical Process Control) charts of a reference sample. The measurement repeatability and reproducibility of the stations are found to be excellent. Moreover, the measured critical current of a strand is found to be almost independent of the test station in which the measurement is performed.

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I. Introduction

The Large Hadron Collider (LHC) is currently under construction at CERN. This machine, mainly intended to provide proton-proton collisions with a center-of-mass energy of 14 TeV [1], is scheduled to be operational in 2006. The LHC accelerator will require more than 8000 superconducting (SC) magnets of various kinds [2]. Among them, the dipole and quadrupole magnets will use SC Cu/NbTi cables for their coils and will be operated in superfluid helium at 1.9 K [3]. For this purpose, around 7000 km of Rutherford-type NbTi cables are currently manufactured at several companies around the world [3]. The SC cables, respectively used for dipole inner layer (01 type) and for dipole outer layer and quadrupole magnets (02 type), are made of 28 and 36 strands. The overall length of the SC strands utilized for LHC cables production will exceed 240 000 km. The main characteristics of 01 and 02 strands are summarized in Table 1.

As a part of acceptance tests of the conductors, the critical current of cable strands is systematically measured at CERN, at 4.2 K in magnetic fields in the 6-8 T range and at 1.9 K between 8 and 11 T. Critical current measurements at 1.9 K are exclusively done at CERN, the strand manufacturers testing only at 4.2 K. These tests are performed on virgin strands (i.e. before cabling) to qualify the multifilamentary billets. After cabling, strands randomly selected and extracted from the cables are tested to qualify the latter. More than 30 000 strand samples are foreseen to be tested in four years.

In this article, the design and the operation of the four strand critical current (I_c) test stations, commissioned at CERN, are described. Moreover, important characteristics of the stations, like repeatability, reproducibility and the agreement of critical current data, as measured on various stations, are discussed.

II. Experimental setup and procedures

The test setup is schematically depicted in Figure 1. The cryostat is a conventional double bath system [4] divided in two parts by a plate made of insulating material (λ-plate). The liquid helium in the upper bath is always at ~ 4.2 K whereas the lower bath can be cooled down to 1.9 K by pumping on a toroidal heat exchanger. For 1.9 K tests, the lower bath temperature is regulated by means of a regulation heater. Automatic ABB software is fully monitoring all the cryogenic operations, including cooling to 4.2 K and 1.9 K and warming up the station. The temperature is controlled by means of two Cernox^{TM} and one germanium probes, which are situated in low-field zones. In such a way, the temperature readings on both Cernox^{TM} probes are not affected by the applied magnetic field. The germanium probe, much more field sensitive and known for its precision and long-term stability [5], is thus used to check the reliability of the Cernox^{TM} probes before the magnetic field is ramped up. The overall uncertainty on temperature reading is ± 7 mK.

In each test station, the magnetic field, produced by means of a SC hybrid Nb_3Sn/NbTi solenoid (100-mm inner bore), can reach 11 T and 13 T, at 4.2 K and 1.9 K respectively. The magnetic field homogeneity was measured to be better than 0.2 % over the relevant surface, on where the strand samples are set out. The magnetic field value was calibrated beforehand by means of NMR probe. The total uncertainty on the magnetic field is 3 mT. The tested strand samples are mounted onto an 85-mm in diameter cylindrical grooved

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mandrel. The angle between the sample grooves and the magnetic field axis is 84°. The sample holder can contain up to 10 samples and is made of a glassfiber epoxy composite (G11). The grooves of the sample mandrel were beforehand covered by PTFE tape to ensure a better contact of the mounted samples on the grooves, thus avoiding premature quenches of extracted strands. During a critical current test, a stable DC power supply (batteries), providing up to 1000 A, supplies the current to the SC strand sample through bronze current leads. The sample current is then measured through a signal coming from a zero-flux current transformer by a multimeter with an overall uncertainty of 0.01 A. The test setup is also composed of a workstation for controlling the whole process, a nanovoltmeter for accurate voltage measurements and a precision multimeter equipped with a scanner card for measuring regularly temperatures, liquid helium level and pressure. All the communications between the workstation and the acquisition data instruments are performed by means of an ANSI/IEEE-488.2 bus, the instruments being coordinated by a LabVIEW™ based program. The acquisition instruments and the temperature probes are regularly calibrated according to Swiss national and secondary standards, respectively, ensuring accurate and consistent results for the four test stations.

At given conditions of temperature and magnetic field, the critical current is determined by ramping up the current flowing within the sample at a constant rate (12.5 A/s) and by recording the voltage measured between two voltage taps separated by a distance of 80 cm. This distance is enough to guarantee a fair signal-to-noise ratio. The typical voltage noise, 0.3 μV, provides a critical current uncertainty less than 0.1 %. The current flows within the sample in such a way that the Lorentz force is acting inwards, i.e. pressing the strand against the sample holder. Additional unwanted voltages, induced by the current ramp or by possible current transfer effects and thermal electromotive forces, are cancelled out by subtracting the baseline voltage from the V-I curve. The corrected data is then fitted with $V = V_c (I/I_c)^n$, where n is determined between E = 0.1 μV/cm and E = 1 μV/cm, and the critical current value is evaluated according to the 10^{-14} Ω.m total section resistivity criterion. For measurements done around 4.2 K, the critical current values are scaled to 4.222 K by means of the well-known linear extrapolation:

$$I_c = I_m \, (T_c - 4.222) / (T_c - T_m) \, , \qquad (1)$$

Where I_c is the critical current at 4.222K, I_m is the critical current measured at the temperature T_m and T_c is the critical temperature as given by Lubell [6].
The critical current is measured as a function of the external magnetic field; no correction for self-field is done. After each current ramp, the V-I curve is automatically analyzed on-line and its validation is considered according to several validation criteria (mainly noise and fit quality). In case the curve is not validated, the program launches an additional measurement. For the sake of quality control, a reference sample is permanently mounted on the sample holder. Its critical current is measured for every magnetic field and compared to Statistical Process Control (SPC) charts of previous measurements. SPC curves of the critical current value versus the test date also provide an estimation of the test station reproducibility.

LabVIEW is a registered trade mark of National Instruments Corporation, USA.

III. Measurement repeatability and reproducibility

For a given critical current station, the measurement repeatability and reproducibility are relevant quality indicators. The repeatability, defined here as the station precision i.e. its ability to provide consistent I_c values when measurements are performed in the same conditions, was evaluated by measuring the critical current in a repetitive way and by observing the I_c data scatter. For this purpose, five successive current ramps were performed at each test station, for several samples and all the considered magnetic fields. The I_c spread was generally found to be less than 0.5 % of the average value for 1.9 K and within 1 % for 4.2 K. The maximal deviation between maximal and minimal I_c values ever reached for the five ramps was 1.3 %.

The station reproducibility is defined as its capacity to provide similar I_c results when the measurements are done in different conditions. The reproducibility can thus be estimated by following the SPC I_c curve of the reference strand as a function of cooldown date. For the four test stations, the deviation between the maximal and minimal I_c values as measured on tens of cooldowns (several months) was always found to be less than 1.5 % for all the considered reference samples and magnetic fields. The critical current scatter was even less than 1 % for 1.9 K measurements.

IV. Comparison between various test stations

For comparing the performances of the CERN test stations, a sample holder, mounted on a sample insert, is kept as a reference mandrel. This holder is regularly tested at the various stations where a few current ramps are systematically measured for every sample and for all temperature and magnetic field conditions. It appears that the various stations agree fairly well with each other, the agreement of critical currents as averaged on every couple of stations being, for each considered sample, within 0.5 % for 1.9 K measurements. This agreement is within 1 % at 4.2 K. The excellent measurement compatibility of the stations is illustrated by Figure 2, where the critical current SPC chart of a given reference sample is shown. The spread of I_c values, as measured for seven months on two different stations, is less than 0.7 %. It appears that the difference in I_c measured results between stations is of the order of single station reproducibility.

It was relevant to compare the CERN test stations to those of other laboratories. For this purpose, a few tens of samples cut from the reference wire spool were sent to Brookhaven National Laboratory, Upton, USA (BNL). These samples were tested there at 4.2 K and the average critical current data were compared to I_c values as averaged over all the spool samples measured at any CERN station. It was found that CERN and BNL values agree within 0.7 % for 8 T. In the case of 6 and 7 T, the agreement was even better than 0.3 %. In addition, several samples of a given SC wire were tested at INFN-LASA, Milan, Italy, at 4.2 K, whereas adjacent samples of the same wire were measured at CERN. It appears that the critical current values as respectively measured at CERN and LASA are fairly compatible, the deviation between them not exceeding 0.5 % in the 6-8 T magnetic field range.

V. Conclusions and perspectives

In this article, the four critical current stations commissioned at CERN, for testing LHC strands at both 4.2 K and 1.9 K, were briefly presented. These facilities are fully operated in an automatic mode for both cryogenics and critical current test. The stations exhibit excellent repeatability and reproducibility. At 1.9 K, both characteristics were found to be better than 1 %. It was also found that the measured critical current is almost independent of the test station, especially at 1.9 K. In addition, comparative 4.2 K measurements done at other laboratories indicated a remarkable compatibility (better than 1 %) with data of CERN stations. Therefore, the CERN facilities appear to be high quality critical current stations. They can provide testing 36 samples per working day, i.e. around 8500 samples per year.

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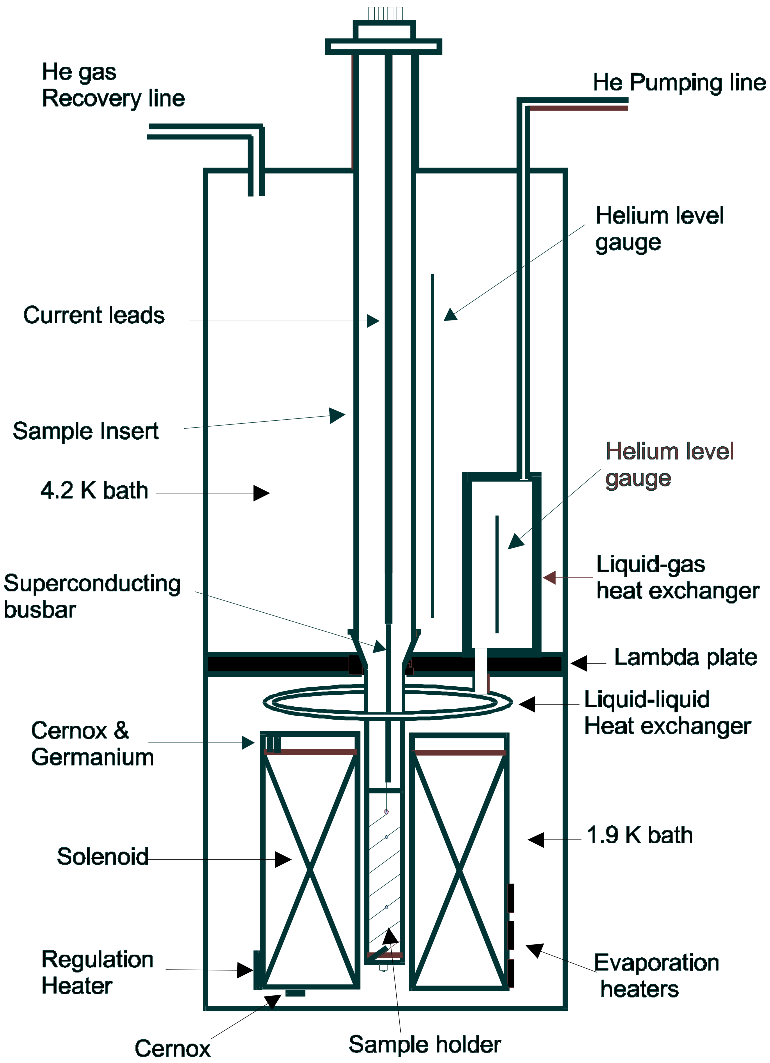
<u>Table 1:</u> Main characteristics of LHC 01 and 02 type SC strands

	01	**02**
Strand diameter [mm]	1.065	0.825
SC filament diameter [μm]	7.0	6.0
Cu to SC ratio	1.65	1.95
Filament twist pitch [mm]	18.0	15.0
Minimum critical current, 1.9K	515 A (10T)	380 A (9T)



<u>Fig. 1:</u> The schematic description of a CERN strand critical current station (see text).

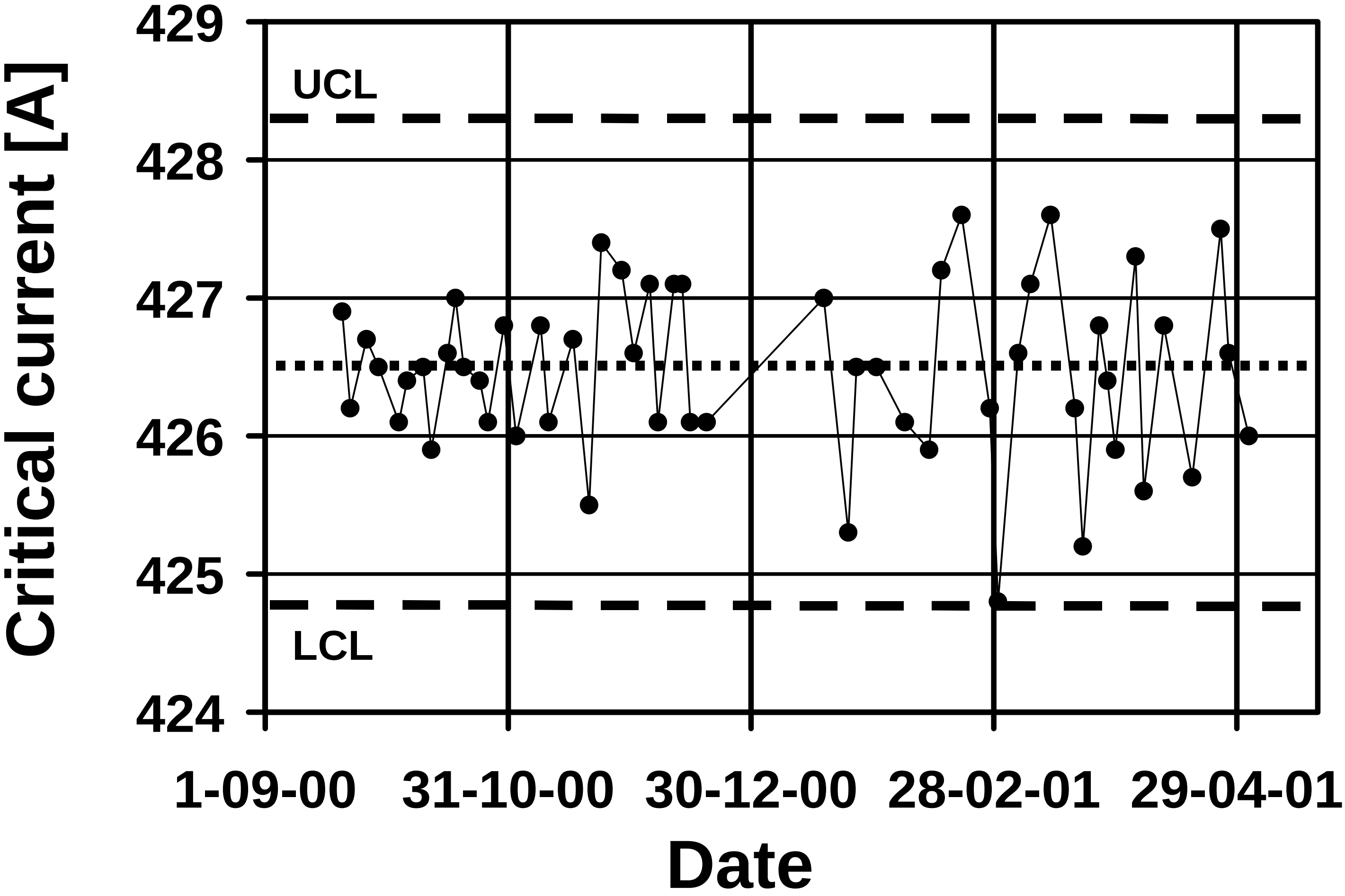


Fig. 2: The critical current SPC chart of a reference sample as measured on two different stations over a seven month period. The dotted line represents the mean value, m, whereas the upper (lower) dashed line shows the UCL (LCL), i.e. the upper (lower) control line. UCL and LCL are defined by ($m \pm 3\sigma$), σ being the standard deviation of the measurements.