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Presented at the 19th International Conference on Magnet Technology (MT19)
18-23 September 2005, Genova, Italy

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Geneva, 19 May 2006

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Index Terms—Residual Resistivity Ratio, RRR, Superconducting Wires, Superconducting Cables, NbTi, Copper

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 [1,2], is scheduled to be operational in 2007. The LHC accelerator will require more than 8000 various superconducting magnets [3]. Among them, the dipole and quadrupole magnets will use superconducting (SC) NbTi cables for their coils and will be operated in superfluid helium at 1.9 K [4,5]. For this purpose, around 7000 km of Rutherford-type NbTi cables are currently mass-produced by six industrial firms around the world. The SC cables, used for dipole inner layer (01 type) and for dipole outer layer and quadrupole magnets (02 type), are made of 28 and 36 strands respectively.

The residual resistivity ratio (RRR) of LHC SC strands is defined as the ratio of resistance at 293 K to the resistance at 10 K [5]. As the resistance of a superconductor (NbTi) is significantly higher than the resistance of copper (more than 30 times at 293 K) and the copper to superconductor volume ratio (Cu/Sc) is about 1.6-2.0, the RRR of SC strands reflects mainly the properties of copper used as matrix material in the

strands (see Fig 1). Therefore the RRR of the LHC strands is

Fig. 1. Typical cross-section of LHC strands ("single stack" technology). one of the quality assurance parameters of the final SC cables directly related with electro-dynamic stability of the magnets and limitation of the hot spot temperature in the coil in case of a quench. The main characteristics and RRR-specifications of 01-type and 02-type strands are summarized in Table 1.

TABLE I
LHC SC STRANDS CHARACTERISTICS

	01-type	02-type
Strand Diameter	1.065 mm	0.825 mm
Cu/Sc ratio	1.6 – 1.7	1.9 – 2.0
RRR of virgin strands before cabling	> 150	> 150
RRR of extracted strands after cabling	> 70	> 70

As a part of the acceptance tests of the conductors, the RRR of SC strands is systematically measured at CERN on virgin strands (i.e. before cabling) to qualify the multifilament billets (strand production units). After cabling, strands randomly selected and extracted from the cable are tested to qualify the cable itself. More than 12000 samples of virgin and extracted strands have already been measured during last five years. The report gives a description of the test station and the

Manuscript received September 20, 2005.

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measurement procedure, and presents the summary of the results over all suppliers, examples of RRR evolution during production and some comparisons between RRR-values of the cables and the magnets.

II. EXPERIMENTAL SETUP AND PROCEDURES

As was mentioned before, RRR of SC samples is the ratio between the electrical resistivity at 293 K ($\sim 20^\circ\text{C}$) and that at the temperature just above the critical temperature T_C which is about 10 K for NbTi wires. The measurement of the electrical resistances of the sample wires is based on the measurement of their UI-curves. The samples are fixed in a window frame fiberglass holder (130x100 mm) and connected in series (see Fig 2). While the current is ramping up step by step trough the samples, the voltage drop on each sample is measured. The electrical resistances are calculated by a least square fit (regression analysis) of the obtained UI-curves in order to

Fig. 2. RRR sample holders.

obtain the best slopes. The nonlinearity of UI-curve is used as one of the test quality criteria to control an ohmic heating in case of a room temperature test and to check a full super-to-normal-conducting transition at a cold test. The maximum number of samples that can be mounted on the holders is 20. The sample length is about 110 mm, while the voltage taps length is about 80 mm. One of the wires is always kept mounted on the holder and is used as a reference wire. The temperature is verified by a calibrated carbon-ceramic resistor [6] fixed close to the reference wire. During the tests the holder is always in horizontal position to minimize the thermal non uniformity along the samples.

All the communications between the workstation and the data acquisition instruments are performed by means of an ANSI/IEEE-488.2(GPIB) bus, the instruments being controlled by a LabVIEWTM based program. The acquisition instruments (Nanovoltmeter KEITHLEY2182, voltmeters KEITHLEY2001 and KEITHLEY2000) are regularly calibrated according to Swiss national standards.

A. Warm test

19 selected samples are fixed on the holder which in turn is

mounted on the “sample insert” - a special support to put a holder into the cryostat for the cold test. The test at room temperature is performed in a specially designed “warm test box” where the temperature is regulated to $20 \pm 0.5^\circ\text{C}$ by a thermostat. The box is designed in such a way that a sample holder being already mounted on the sample insert can be installed there. Excitation current is varied from 0 to 1 A, while the voltage drops are in the range of 1-5 mV. The used range of excitation satisfies the requirements of sufficient sensitivity and negligible ohmic heating.

B. Cold test

The cold measurements take place in a conventional 4.2 K liquid helium cryostat, which is also used for the contact (interstrand) resistance measurements of LHC cables [7]. Automatic ABB software is fully controlling all the cryogenic operations, including cooling to 4.2 K, filling the cryostat with liquid helium to the required level and warming up the station. The schematic description of a cold test is shown in Fig 3.

Fig. 3. The schematic description of a RRR station (cold test).

The resistance at low temperature is measured by warming up the samples from 4.2 K to a temperature just above the superconductor critical temperature (about 10 K for LHC strands). This condition is achieved by turning on the heater installed on an intermediate vertical tube to heat up the helium gas around the samples. The resistance of a reference wire and the temperature close to samples are measured during the warm up to ensure that the transition to normal state occurs and are used to trigger the UI-curve scanning of all mounted samples. The current is varied from 1 A up to 10 A, while the signal voltages are about 0.01-0.2 mV.

The UI-measurement takes a couple of minutes while the temperature does not deviate more than 0.5 K. The servomotor located on the top part of the insert allows to move down a holder, i.e. put the samples back to

superconductor state, and to repeat a test procedure in case of necessity.

Finally, an automatic analysis is applied on the measured data to get the resistances from the UI-curve slopes. The RRR-values are calculated as the ratio R_{293K}/R_{10K} with an estimated total uncertainty of $\pm 1\%$, where R_{293K} and R_{10K} are the resistances at room and cold temperatures respectively. Then the obtained values are validated on condition the requirements to the linearity of UI-curves, the temperature spread and reference sample data. At the same time the valid results are loaded to the central Oracle database to be used in the quality control following. The RRR-test facility can provide testing 38 samples per working day, i.e. around 9000 samples per year.

III. SUMMARY OF RRR-MEASUREMENTS ON LHC STRANDS

During the last five years more than 12000 samples of virgin and extracted LHC SC strands coming from six suppliers have been tested at CERN. The results of measurements (average, standard deviation and number of samples tested) are summarized in the Table II. The first column contains the results of measurements on virgin strands after the “annealing”, which is defined as a heat treatment at moderate temperature for restoring a high value of RRR before coating and cabling [5]. Those values reflect the initial purity of the raw copper and the state of annealing as well. They are taken into account in the billet (SC strand production unit) acceptance procedure. About 30 billets with low RRR-values have been detected.

TABLE II

AVERAGE RRR, STANDARD DEVIATION AND NUMBER OF SAMPLES TESTED			
Type& Supplier	Virgin strands	Extracted from cables just after cabling	Extracted from cables after heat treatment
01B	158 $\pm$ 17 (2250)	83.1 $\pm$ 4.8 (3200)	216 $\pm$ 22 (2280)
01E	121 $\pm$ 07 (1530)	73.2 $\pm$ 4.5 (1950)	167 $\pm$ 13 (1200)
02B	176 $\pm$ 19 (2150)	94.8 $\pm$ 4.8 (2350)	234 $\pm$ 25 (1870)
02C	133 $\pm$ 23 (2950)	85.3 $\pm$ 6.0 (900)	192 $\pm$ 16 (1100)
02D	190 $\pm$ 22 (800)	87.9 $\pm$ 3.3 (820)	173 $\pm$ 35 (800)
02G	147 $\pm$ 14 (1430)	81.6 $\pm$ 2.8 (850)	161 $\pm$ 16 (1100)
02K	172 $\pm$ 12 (1380)	88.7 $\pm$ 3.5 (840)	179 $\pm$ 14 (1200)

The second column contains the RRR-values of the strands extracted from SC cable just after the cabling. Those tests are done by the firms and their values reflect the “cold work” due to the cabling. The results presented in last column have been measured on the strands extracted from SC cables after the final heat treatment done at 200°C during few hours to control the interstrand contact resistance, i.e. from the cables which are ready to be sent to the magnet manufactures. Those data can be used to estimate RRR-values of LHC magnets, can be taken into account to calculate the hot spot temperature in case of quench, etc.

To control the annealing process during SC strand production, the RRR of strand samples is also measured by supplier companies. So the RRR results on virgin strands done by CERN are used, besides the billet acceptance, to

crosscheck of RRR data sent by companies. As an example, the comparison of overall measurements on virgin strands is presented in Fig 4. The picture shows a fair correlation, about 0.93, between CERN and companies results.

Fig. 4. Correlation between RRR-values measured on virgin strands by companies and by CERN.

The figures 5, 6 and 7 presents the RRR-value of SC strands versus cable production id-code for the different technological stages (01B, 02B, 02K types taken as an example). The upper points are the RRR of final cables, the lower points are the RRR of cables just after cabling and the middle ones are the averaged RRR of virgin strands which have been used for cabling of the corresponding cable. The marked difference in the figures for the shift value between RRR curves of virgin strands (middle curves) and cable strands (upper curves) can be explained by technological specificities, as an annealing of virgin strands, heat treatment duration of cables, etc.

Fig. 5. RRR of LHC SC strands (01B type) versus cable production id for the different production stages.

Fig. 6. RRR of LHC SC strands (02B type) versus cable production id for the different production stages.

Fig. 7. RRR of LHC SC strands (02K type) versus cable production id for the different production stages.

IV. COMPARISON WITH MAGNET RRR

The figure 8 presents the comparison between measured RRR-values of the dipole magnets for the different manufactures with the calculated values based on RRR of the cables.

Fig. 8. Comparison of measured RRR-values of dipole magnets with values calculated from RRR on extracted strands.

V. CONCLUSION

A test facility for the mass measurement of RRR on superconducting NbTi strands has been developed and successfully operated at CERN. Capacity of the described RRR test facility is 38 samples per working day, i.e. around 9000 samples per year. This capacity fully satisfied the needs in the RRR-tests foreseen for the acceptance of LHC SC strands and for the final approval of LHC cables.

Experience of thousands of tests shows good precision (about 1%) and reliability of the developed facility. Results show a fair correlation with the measurements done by the companies and reflect well the technological process of cable production (strand annealing, cabling, cable heat treatment). In the near future it is foreseen to adapt the test environment to measure Nb₃Sn superconducting samples.

ACKNOWLEDGMENT

The author would like to thank D. Leroy, L. Oberli, D. Richter and G. Cavallari for their kind and useful collaboration. The author thanks M. Seydoux, J. Cuvet, A. Bastos, P. Jacquot, M. Pouchoux and J.-S. Denis for invaluable technical support, thanks N. Emelianenko and E. Charifoullina for database support and thanks E. Floch and P. Pugnât for dipoles RRR data.

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