MEASUREMENT OF THE RESIDUAL RESISTIVITY RATIO OF THE BUS BARS COPPER STABILIZER OF THE 13 kA CIRCUITS OF THE LHC

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Abstract

After the incident of September 2008, the operational beam energy of the LHC has been set to 3.5 TeV, since not all joints of the superconducting (SC) bus bars between magnets have the required quality for 7 TeV operation. This decision is based on simulations to determine the safe current in the main dipole and quadrupole circuits, reproducing the thermal behaviour of a quenched superconducting joint by taking into account all relevant factors that affect a possible thermal runaway. One important parameter is the Residual Resistivity Ratio (RRR) of the copper stabilizer of the bus bar connecting the superconducting magnets. A dedicated campaign to measure the RRR for the main 13 kA circuits of the LHC in all sectors was performed during the Christmas stop in December 2010 and January 2011. The measurement method as well as the data analysis and results are presented in this paper.

INTRODUCTION

The total length of the bus bars in the LHC amounts to roughly 50 km for the RB circuits and 100 km for the RQ circuits. Voltages are measured over about 2000 so-called 'segments', covering lengths of typically 30-200 m. Two adjacent bus bars are soldered together as shown in Fig. 1. The detailed analysis after the 2008 incident [1] has raised the problem of bus bar splices that do not have the required quality, which is now of major concern for running the LHC at high energy. In a good splice [2], the resistance between the two SC cables should be less than 0.6 nΩ and the copper splice stabilizer and the bus stabilizer (on either side of the splice) should work as a continuous electrical shunt to the cables. This is achieved when the SnAg solder fills all the voids in and around the splice (Fig. 1).

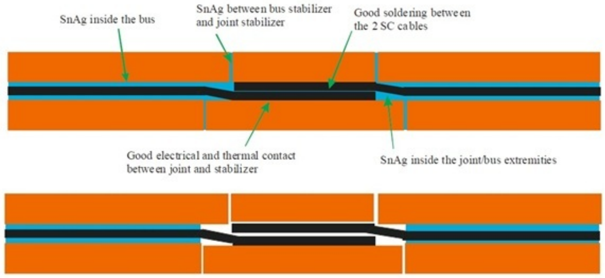

Figure 1: Schematic view of a 13 kA splice with and without good solder filling.

If there is a lack of soldering material, a quench in the splice can lead to a very fast thermal runaway, generated by the heating in the super-conducting cable and the bad thermal and electrical contact between cable and copper stabilizer. In this case, the current will not flow continuously through the joint stabilizer but will be forced to flow in the SC cables above the critical temperature, showing a significantly higher resistance then copper.

Many simulations [3] have been performed varying the RRR and cooling conditions, in order to find the worst case scenario, i.e. the case that gives the lowest thermal runaway current for a given joint resistance. The purpose of the present work is to determine the 'average' RRR of the bus bar, which is then used as realistic input for safe current simulations.

The typical values of the RRR of the LHC copper stabilizers are in the range from 200 to 300.

RRR MEASUREMENT CAMPAIGN

RRR Definition

The RRR of copper is defined as the ratio of its resistivity at 293 K to the resistivity at 4.2 K.

$$\mathrm{RRR} = \rho_{Cu}(293\ K)/\ \rho_{Cu}(4.2\ K) \qquad (1)$$

$$\rho_{Cu} = \left(\frac{c_0}{RRR} + \frac{1}{c_1/T^5 + c_2/T^3 + c_3/T}\right) * 10^{-8} + \alpha_{\mathrm{M}} * B \qquad (2)$$

Eq. 2 shows the dependency of the resistivity on the RRR, the temperature T and the magnetic field B, given the numeric constants c_0, c_1, c_2, c_3 and the magneto-resistivity α_{M}. For these measurements, which were performed with relatively low currents (10 A or 20 A), the contribution given by the magnetic field is considered to be negligible.

As the resistivity of a superconductor (NbTi) is significantly higher than the resistivity of copper (more than 30 times at 293 K), measurements performed above the critical temperature (which for NbTi in zero magnetic field and zero current density is 9.3 K) mainly reflect the properties of the bus bar copper stabilizer.

RRR Measurements

It was decided to measure the RRR in all of the 8 sectors of the LHC [4]. Measuring the RRR of the bus bar stabilizer in situ in the tunnel is not an easy task and requires the combined effort of different teams working on the LHC (i.e. cryogenics, power converters, magnet protection, operation,...). The campaign took two days per sector, keeping the necessary conditions for the measurements for an extended time window during the technical stop of the machine from December 2010 to January 2011. It also required many hours of work in the

LHC tunnel in order to set up the necessary measurement equipment.

The critical importance of this study for CERN justifies the large effort spent for these measurements.

Given the definition of RRR in Eq. 1, two sets of data are necessary, each corresponding to one of the two reference temperatures of the definition; data at a temperature around 290 K will be referred to as ‘warm' whereas data at a temperature around 4 K (in principle) as ‘cold’. Due to the impossibility of warming up all the sectors of the machine for the lack of enough storing helium facilities, only five of them were warmed up to about 290 K. The other three only reached a maximum temperature of about 80 K (sectors 2-3, 7-8 and 8-1). Furthermore, for the ‘cold’ data, it would be impossible to measure the RRR of the copper stabilizer at 4 K since the critical temperature would not be reached and the current would still flow in the SC cable, so the RRR was effectively evaluated between 10 K and 20 K (see Fig. 2).

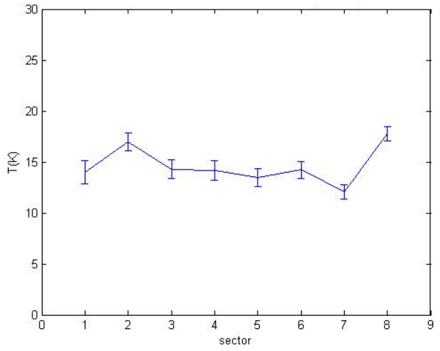

Figure 2: Average temperatures and standard deviations of ‘cold’ data used for the RRR evaluation in the 8 LHC sectors.

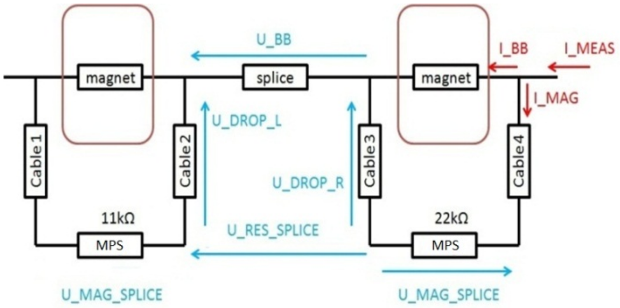

Figure 3: RRR measurement scheme (cable1 to cable4 are instrumentation cables).

The voltage of all bus bar segments in a sector (leading to the determination of resistance) is measured using the magnet protection system (MPS). The measured quantities are U_RES_SPLICE and U_MAG_SPLICE. A square wave shaped current (I _MEAS) with an average period of 10 minutes and a 10 A or 20 A amplitude flows in the bus bars generating a voltage drop (U_BB), the effective target of the measurement (Fig. 3). Due to the finite resistance of the measurement devices, part of the current (I_MAG) flows in the instrumentation cables, generating a voltage drop (U_DROP) which needs to be taken into account for a correct evaluation of the bus bar voltage (Eq. 3).

$$\mathrm{U\_BB}=\mathrm{U\_RES\_SPLICE}+(\mathrm{U\_DROP\_L}-\mathrm{U\_DROP\_R}) \quad (3)$$

The latter allows the computation of the current in the instrumentation cables, given the values of input resistance of the measuring devices (either 11 kΩ or 22 kΩ). These low values clearly show that the MPS was not designed for this type of measurement.

CALIBRATION

A calibration campaign was performed in order to understand the required corrections: as mentioned in the previous paragraph, a significant part of the voltage recorded by the MPS is not due to a voltage drop in the bus bar segment, but due to a voltage drop in the instrumentation cables connected to the voltage measuring device. This quantity is proportional to the cable lengths and their resistivity. Typical amplitudes for measured voltages for U_RES_SPLICE are of the order of 10^{-4} V. For U_MAG_SPLICE standard values are of the order of 10^{-1} V instead. The resulting U_BB is roughly half of the recorded U_RES_SPLICE (Fig. 4).

The calibration was performed by installing a series of ‘patches' in about 10% of the bus bar segments of a LHC sector to eliminate the voltage drops in the instrumentation cables and to be able to measure directly U_BB. This calibration gave a value for the resistivity of the instrumentation cables of 87 mΩ/m with a preliminary uncertainty of 5%. The analysis which is presented considers this reference value for the resistivity and thus does not take into account differences in the ambient temperature of the tunnel between different sectors.

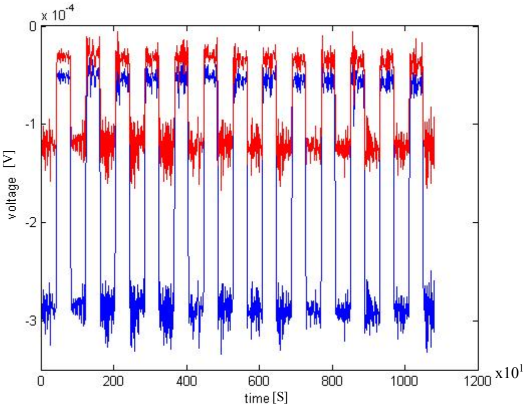

Figure 4: Computed bus bar voltage U_BB (red) compared to the U_RES_SPLICE signal (blue).

DATA ANALYSIS

Square wave current signals are applied and it is important to avoid calculating the resistance close to the edges of the square signals. Other important factors to be taken into account in the analysis are linked to the non-ideal shape of the waves, due to physical imperfections of the hardware components (that can cause ripple and spikes) and to noise.

The adopted solutions to limit these problems were:

- Signal filtering to exclude periods immediately after or before the edges.
- Selection of measurement periods less affected by noise (where possible).

Typically, out of 3 hours of data, about 110 minutes with a 10 seconds frequency are used for data analysis.

According to the definition (Eq. 1), the RRR computation is then based on the extraction of two sets of data, each corresponding to one of the two reference temperatures of the definition. The selected time windows (TW) for each sector were chosen according to cryogenic settings, since signal measurements are only significant above the critical temperature. Several attempts were made to identify the most reliable intervals, in order to have an average temperature safely above it. Two time windows per sector have been selected to exploit the redundancy on data and increase the reliability of the results.

RESULTS AND CONCLUSIONS

The measurements were performed separately for the dipole and quadrupole circuits. Table 1 summarizes data and statistics collected for each sector and for each of the two chosen TW. Results are very coherent within the two selected TW: the RRR values are very close in the two cases and are in the expected range (200-300). RRR values for quadrupole circuits are consistently higher than the ones for dipole circuits: the explanation of this effect, is the higher percentage of SnAg, which has in turn a high RRR, in quadrupole bus bars compared to the ones for dipoles.

Fig. 5 shows the general trend of the RRR in all the 8 sectors of the LHC, shown as a function of the bus bar segment. Several out-of-range points are noticed: some of them are due to different temperature profiles within the same sector. It has been estimated that a temperature drift of 5 K can lead to a shift in the average RRR in a sector of about 30. Observed temperature variations within one sector go from 5 K to 13 K for a given TW.

Some other cases (manually filtered and set to zero) are due to the effective lack of parameters in the database records (i.e. cable lengths) or missing data (mainly the warm temperatures needed for the RRR computation).

As explained in the introduction, the purpose of the measurement was not to determine the single RRR of each bus bar, which is not feasible with acceptable accuracy given the available instrumentation, but to deduce the average RRR of the LHC copper stabilizer for safe current simulations. Furthermore bus bars were produced in batches, therefore the same 'average' quality of copper is expected within a reasonable range.

The results of the measured RRR values were one of the factors that brought to the recent decision of increasing the operational energy of the LHC from 3.5 TeV to 4 TeV.

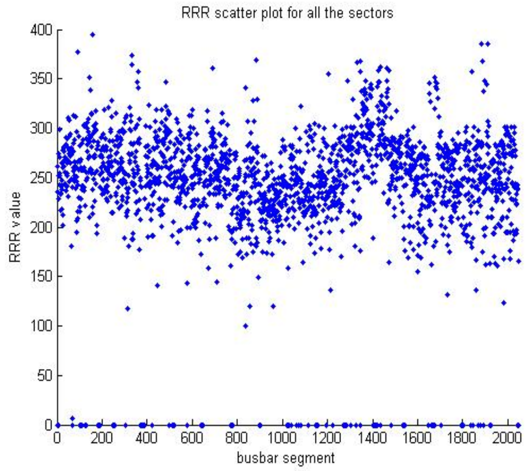

Figure 5: RRR as a function of the bus bar segment.

Table 1: RRR average values and standard deviations in the two selected time windows (TW).

SECTOR	CIRCUIT	FIRST TW	SECOND TW
1-2	DIPOLE	261-32	260-35
	QUADRUPOLE	267-29	269-31
2-3	DIPOLE	260-40	260-39
	QUADRUPOLE	266-34	262-31
3-4	DIPOLE	247-35	248-35
	QUADRUPOLE	263-25	264-23
4-5	DIPOLE	228-35	230-36
	QUADRUPOLE	239-30	240-31
5-6	DIPOLE	240-41	231-26
	QUADRUPOLE	281-41	262-28
6-7	DIPOLE	285-39	268-31
	QUADRUPOLE	301-48	279-33
7-8	DIPOLE	231-31	230-32
	QUADRUPOLE	276-25	277-25
8-1	DIPOLE	233-44	232-42
	QUADRUPOLE	273-19	273-19

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