SPLICE RESISTANCE MEASUREMENTS IN THE LHC MAIN SUPERCONDUCTING MAGNET CIRCUITS BY THE NEW QUENCH PROTECTION SYSTEM

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Abstract

The interconnections between the LHC main magnets are made of soldered joints (splices) of two superconducting cables stabilized by a copper bus-bar. After the 2008 LHC incident, caused by a defective interconnection, a new layer of high resolution magnet circuit quench protection (nQPS) has been developed and integrated with the existing systems. It allowed mapping of the resistances of all superconducting splices during the 2009 commissioning campaign. Since April 2010, when the LHC was successfully restarted at 3.5 TeV, every bus bar interconnection is constantly monitored by the nQPS electronics. The acquired data are saved to the LHC Logging Database. The paper will briefly describe the data analysis method and will present the results from the two years of resistance measurements. Although no splice was found with resistance higher than 3.3 nΩ and no significant degradation in time was observed so far, the monitoring of splices will stay active till the end of LHC 4 TeV run. The detected outliers will be repaired during the Splice Consolidation Campaign in 2013-2014.

INTRODUCTION

The main dipole and quad magnets in each of the eight sectors of the LHC are powered in series. Each main dipole circuit (RB) consists of 154 magnets and 156 bus-bar segments. The quad circuits (RQ) consist of 47 or 51 magnets and 96 or 104 bus-bar segments respectively. Both types of bus-bars contain a single 15.1x1.5 mm^2 Nb-Ti Rutherford cable in the center of the copper bar. The only difference is the total bus-bar cross section which is 20x16 mm^2 for RB circuits and 20x10 mm^2 for RQ circuits [1]. The 10307 connections between bus-bars are soldered by inductive heating using Sn96Ag4 alloy. During this process the two superconducting cables are connected (spliced) with an overlap of 120 mm. The expected average splice resistance R_{spl} is about 0.3 nΩ at 1.9 K with the nominal acceptance limit of 0.6 nΩ set for the LHC. The number of splices in a single bus-bar segment varies from 2 to 6 in RB circuits and from 5 up to 32 in RQ circuits (Table 1).

Table 1: Bus-bars in the LHC Main Magnet Circuits

Circuit	mm^2	Num	Splices	Majority
RB	20x16	1248	2 - 6	2(30%)&3(65%)
RQ	20x10	800	5 - 32	8(91%)

The accident in LHC in September 2008 [2] started in one of the RB bus bars, where an excessive resistance, most likely in the splice between two SC cables due to the lack of solder, caused the joint to quench. In a combination with a bad contact between cables and copper stabilizing bus-bar this resulted in a thermal run away at about 8.7 kA and finally caused a significant destruction of the magnet system in the LHC tunnel. As a consequence of the accident, one of the major consolidation activities for the LHC during the shutdown 2008-09 was the installation of a new layer of magnet circuit protection (nQPS) [3,4,5] in order to provide an early warning for the superconducting bus-bars that develop excessive resistance. In addition to the main protection functionality, the nQPS provides data for continuous storing to the LHC logging database from where the measured voltages are extracted for splice resistance calculations.

MEASUREMENT DETAILS

nQPS: Main Features and Functionality

The new layer of magnet Quench Protection System (nQPS) consists of 436 electronic crates distributed along the 27km LHC tunnel from where every of 2048 main magnet bus-bar segments is monitored by the so called DQQBS boards. The board design is based on an ADuC834™ micro-converter including a 24bit ΣΔ ADC. The two redundant boards are integrated on a single PCB. Each board has two analogue channels U_BUS and U_MAG which share a single ADC. The DAQ sampling frequency is 5 Hz. Both channels are filtered with a 50 point moving average filter which gives effectively a 10 s integration time (Table 2).

Table 2: nQPS DQQBS Board Characteristics

Channel	Range	LSB	Sampling	Filtering
U_BUS	±12.8 mV	1.5 nV	5 Hz	10 s
U_MAG	±15.9 V	1.9 µV	5 Hz	10 s

The U_MAG is used for the compensation of the inductive bus-bar voltages during ramps by measuring the voltage drop across the adjacent magnet. The quench detection threshold on a compensated bus-bar signal is set to 500 µV.

The Background Noise

Fig. 1 illustrates the typical background noise shape of the voltages measured by a DQQBS board on one of the LHC magnet bus-bar segments at a constant current. Note that every point on the plot is already a 10 s moving

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average of 5 Hz samplings, which is essential to fulfil the requirement of 300 - 500 μV threshold level [7].

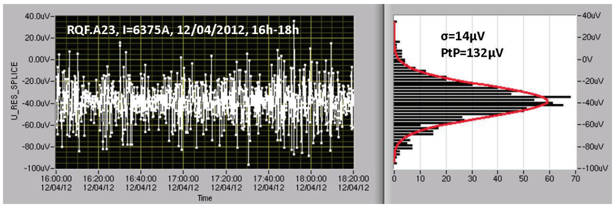

Figure 1: Voltage drops versus time measured by DQQBS board on one of the quad bus-bar segments at 6.4 kA.

The typical noise levels picked up for the different LHC sub-sectors are summarized in Table 3. Different noise levels for dipoles and quads are explained by different bus-bars segment lengths, which are about 30-40 m for dipoles and about 100 m for quads.

Table 3: Peak-to-Peak Noise Amplitudes in μV picked up by nQPS boards in the LHC Tunnel

Sector	12	23	34	45	56	67	78	81
RB	70	50	60	30	20	50	85	75
RQ	175	135	140	85	60	130	200	210

Resistance Measurements

During the 2009-2010 LHC commission campaign [4,5], dedicated powering cycles, the so called pyramids, up to 2 kA and 5 kA, were performed on all LHC main magnet circuits. These measurements allowed evaluating the superconducting bus-bar segment resistances with unprecedented resolution better than 1nΩ in a quite challenging signal to noise conditions. The nQPS data was collected during a number of steady current steps during the current ramping (each of 10-12 steps at about 10-20 min).

Since April 2010, when the LHC was successfully restarted at 3.5TeV, the bus-bars resistance monitoring is done in such a way that every "long enough" powering plateau is automatically detected and analysed. The resistance calculations are triggered if the LHC operates about one hour at injection level and stays more than one hour at top energy afterwards (see Table 4 for LHC operation modes).

Table 4: The LHC Main Magnet Operation Modes

Circuit	Injection	3.5TeV	4TeV
RB	757A	5890A	6730A
RQD/F	685/720A	5340/5580A	6100/6390A

In both cases, the pyramid or ramp to top energy, the bus-bar segment resistances $R_{segment}$ are calculated by a linear fit of *U(I)*-curves which are constructed from the acquired *U(t)* and *I(t)* time series taking into account only the plateau points. The current data *I(t)* is provided by the controllers of the LHC power converters with an accuracy of about 2 ppm [6]. In total, the bus-bar resistances have been calculated from about 500 ramps of the LHC beam operations in 2010 and 2011.

RESULTS

The overview of all measured resistances of the LHC main magnet bus-bars based on two years statistics is presented in Fig. 3. The average measurement errors are about 0.10±0.02 nΩ for the dipoles and 0.12±0.03 nΩ for the quads. Since each bus-bar segment contains *n* splices (see Table 1) it is hence not possible to measure the resistance of an individual splice. However, an estimate of the maximum splice resistance in a segment can be made assuming that the excess is localized in one splice only, so $R_{spl,max} = R_{segment} - (n-1) * R_{spl,avg}$, where $R_{spl,avg}$ is the average splice resistance. The average splice resistance $R_{spl,avg}$ is about 0.30±0.03 nΩ, both for the RB (see Fig. 2) and RQ. In case of quads the number of splices per segment is corrected due to the specific design of the protection voltage taps - part of internal joints of two adjacent magnets is included in the bas-bar segments. The correction estimated by comparing the resistances of 6 and 8 splice segments is about 2x0.20 nΩ.

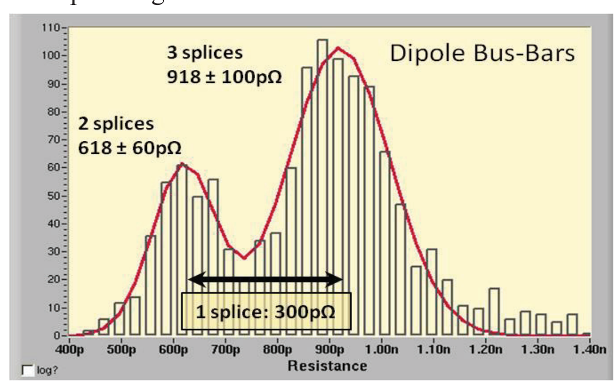

Figure 2: Gaussian fit of the dipole bus-bar resistances where 368 segments have 2 and 816 have 3 splices.

Fig. 4 and Fig. 5 summarise the current status of measured maximum splice resistances of the LHC main magnet bus-bar segments. The highest splice resistance is 2.70±0.09 nΩ for the dipole and 3.30±0.13 nΩ for the quad bus-bars. The results of the quads have a larger spread due to the higher splice number per segment. About 3% of the splices have $R_{spl,max} > R_{spl,avg} + 3\sigma$. These outliers cause no problem for the LHC operation, as their values are still well below the maximum allowable resistance of about 20 nΩ at 13 kA [7]. However a high splice resistance might indicate a mechanical weakness of the joint due to an improper soldering process, and deterioration of that over time can therefore not be excluded. It is important to notice that the two years long monitoring of the splice resistances from each high current plateau did not show any degradation of these splices so far (Fig. 6).

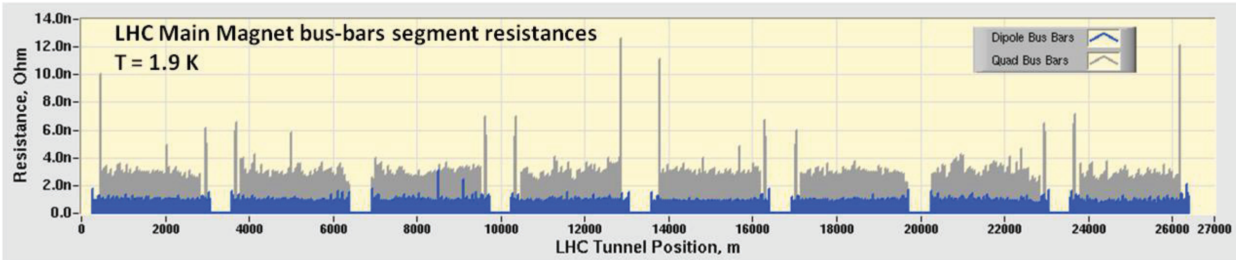

Figure 3: 1248 dipole and 800 quadrupole bus-bar resistances measured at 1.9K versus tunnel position.

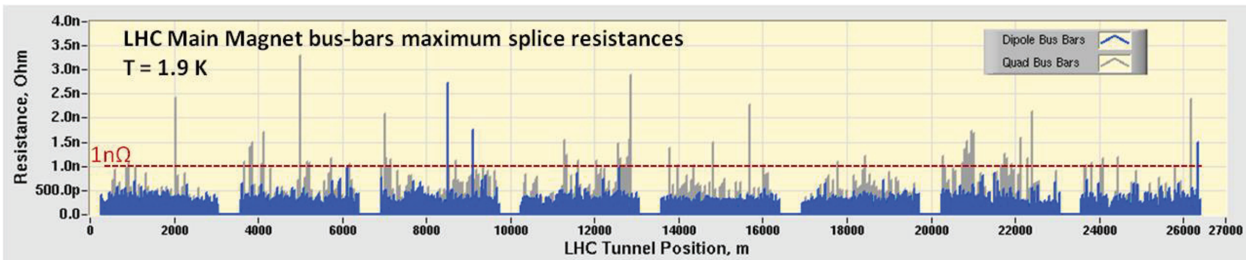

Figure 4: The maximum splice resistances $R_{spl,max}$ versus tunnel position, where $R_{spl,max} = R_{segment} - (n-1) * R_{spl,aver}$.

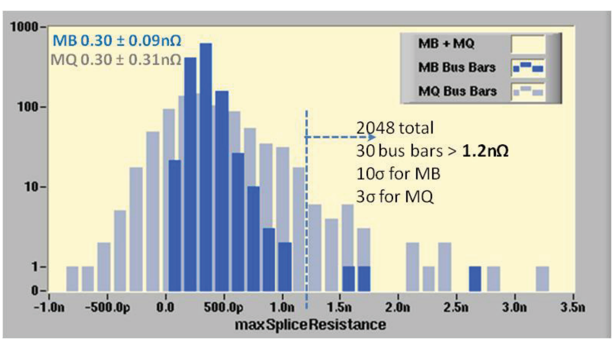

Figure 5: Distribution of maximum splice resistances in RB and RQ bus-bar segments of the LHC.

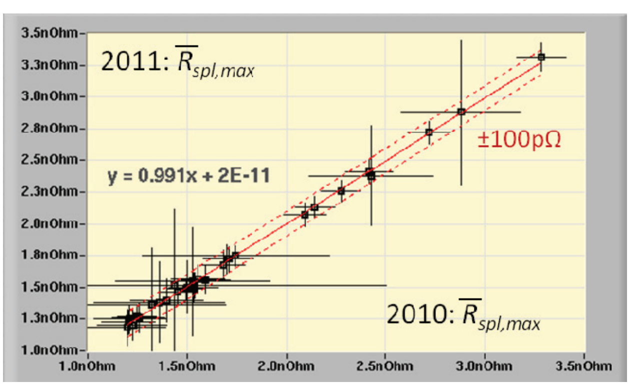

Figure 6: The 30 highest LHC bus-bar splice resistances at the end of 2011 versus the end of 2010.

CONCLUSIONS

Thanks to the new layer of the magnet circuit quench protection system (nQPS), which has been developed, installed and successfully commissioned in 2009, the LHC Main Magnet bus-bar segment resistances are continuously being measured during the LHC operations at 1.9 K. This procedure allowed detecting an excessive resistance of superconducting splices with a high resolution. Although these outliers cause no problem for operation up to 13 kA, they will be monitored for possible deteriorations until the long shutdown in 2013-2014 and will then be repaired.

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