Resistance of splices in the LHC Main Superconducting Magnet Circuits at 1.9 K

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Abstract

The interconnections between the LHC main magnets are made of soldered joints (**splices**) of two SC Rutherford cables, stabilized by a copper busbar. In 2009, a number of splices were found not properly stabilized and could have suffered a thermal runaway in case of quench at high current. The LHC was therefore operated at reduced energy and all joints were continuously monitored by a newly installed layer of the Quench Protection System (nQPS). During the first Long Shutdown (LS1) in 2013/14 the high-current busbar joints were consolidated to allow a safe operation of the LHC at its design energy, i.e. 14 TeV. The SMACC project (Superconducting Magnets And Circuits Consolidation) has coordinated the consolidation of the 10306 13 kA busbar splices. Since 2015, the LHC is successfully operated at an energy of 13 TeV.

SC Circuits, Splices, LS1, SMACC

Table I: Busbars in the LHC Main Magnet Circuits

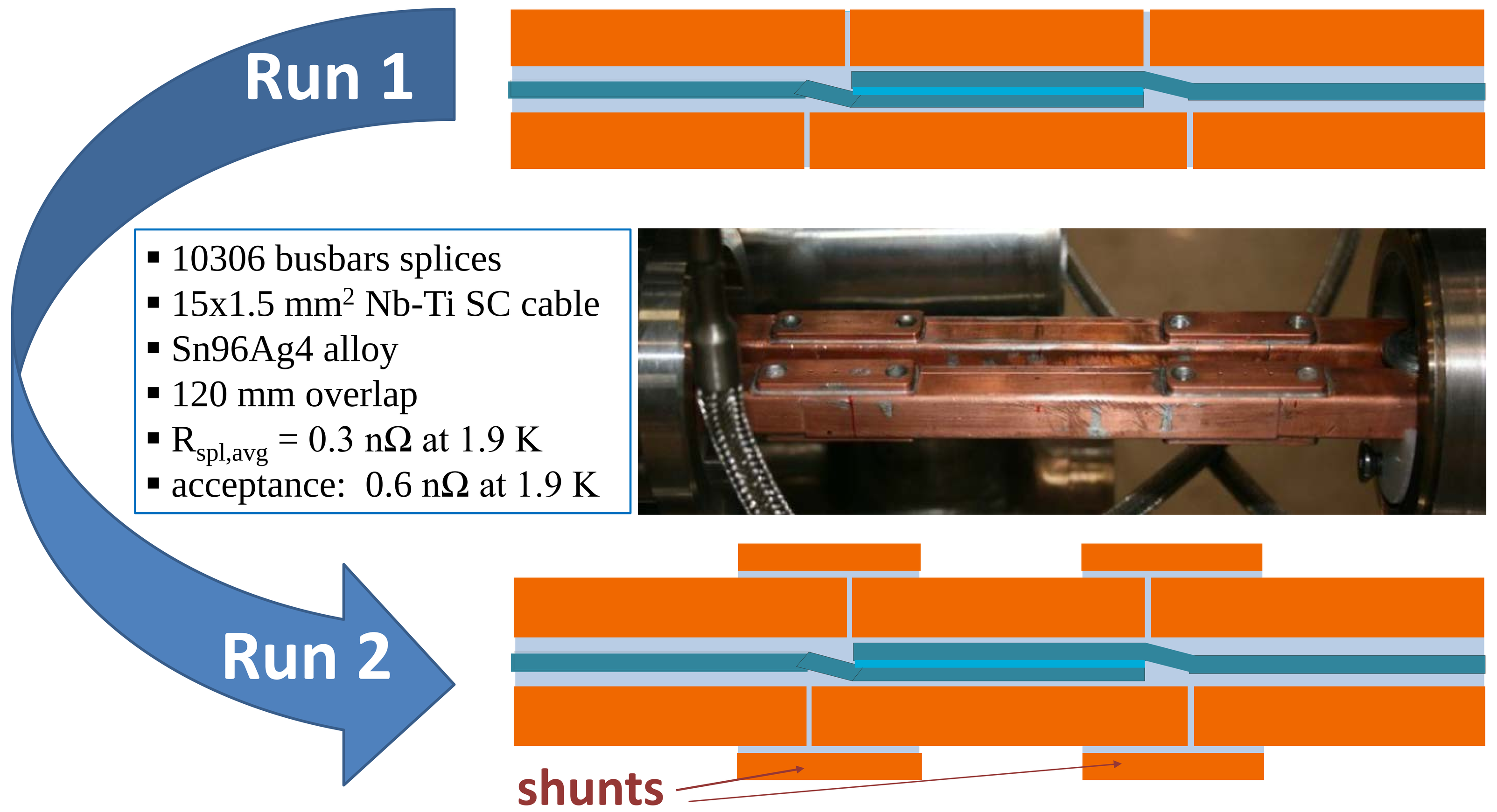
Circuit	Busbar cross-section	Num of magnets	Num of busbar segments	Num of splices per segment
RB	20 x 16 mm²	1232	1248	2 - 6
RQD/F	20 x 10 mm²	392	800	5 – 32/21*

RB corresponds to the main dipole circuit,
RQD/F to the main quadrupole circuits (defocusing and focusing).
* The 32 splices busbar segments have been shortened during LS1.

Table II: LHC Main Magnet Circuits Operation Modes

Circuit	Injection	3.5 TeV Run 1	4 TeV Run 1	6.5 TeV Run 2
RB	757 A	5890 A	6730 A	10975 A
RQD	685 A	5340 A	6100 A	9915 A
RQF	720 A	5580 A	6390 A	10365 A

Run 1 is the period between April 2010 and February 2013, while Run 2 is the period between April 2015 and end of 2018.

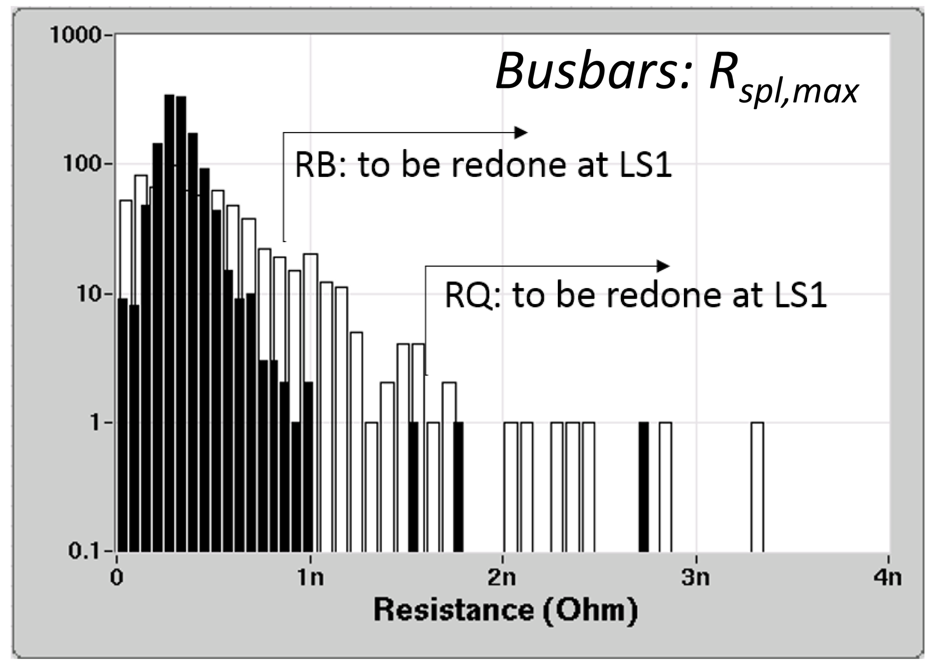


- 10306 busbars splices
- 15x1.5 mm² Nb-Ti SC cable
- Sn96Ag4 alloy
- 120 mm overlap
- $R_{spl,avg}$ = 0.3 nΩ at 1.9 K
- acceptance: 0.6 nΩ at 1.9 K

Conclusion

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 busbar segment resistances are continuously being measured during LHC operation at 1.9 K. This procedure allowed measuring all segment resistances with a high resolution, and detecting excessive resistance of superconducting splices. While these outliers cause no problem for operation up to 13 kA following the very successful splice consolidation project during the first LHC Long Shutdown (SMACC), they will continue to be monitored for signs of possible deteriorations.

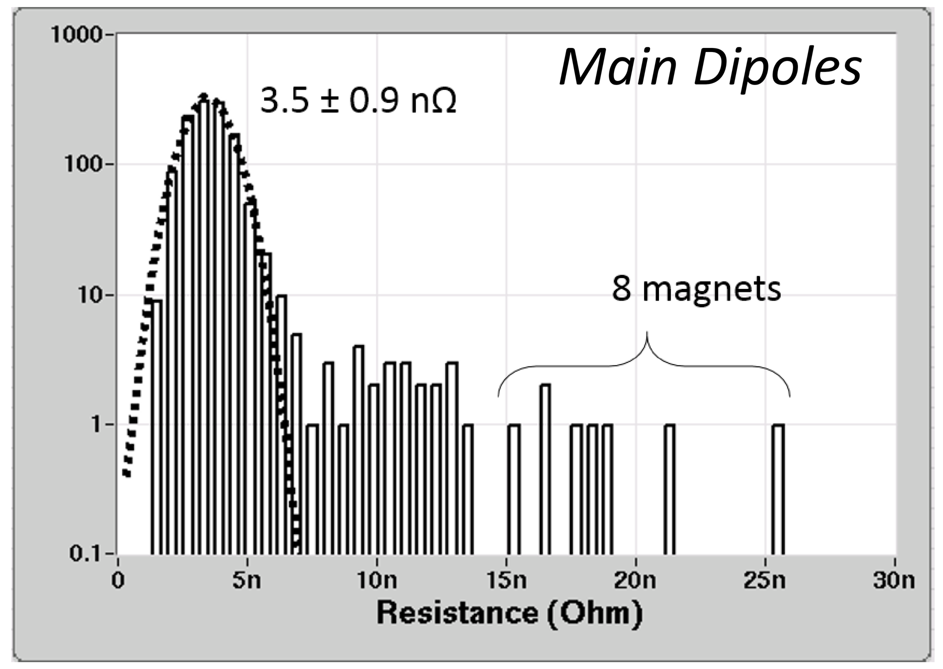
Measurements results



$R_{spl,max}$= 1.8 nΩ

$R_{spl,max}$= 2.7 nΩ

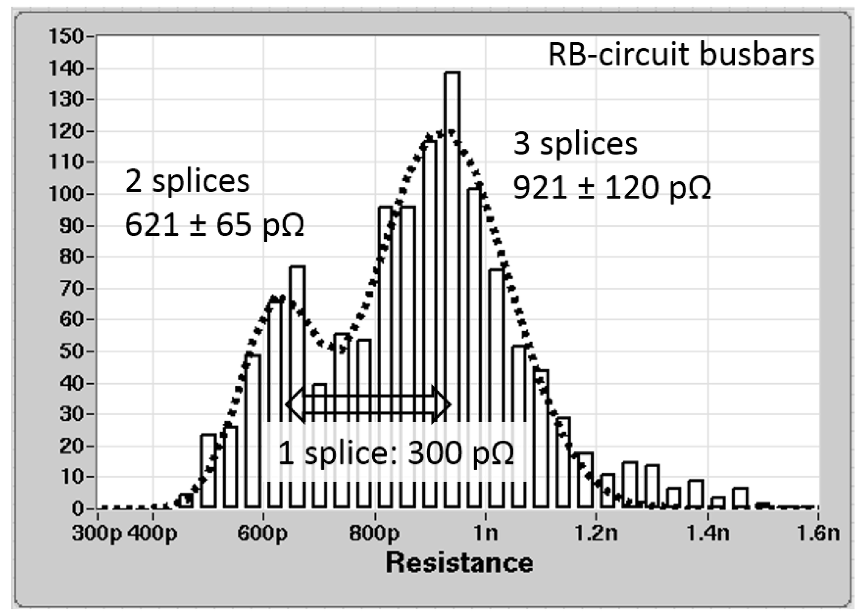
The $R_{spl,max}$ in a segment can be conservatively estimated assuming that the excess is localized in one splice only, i.e. $R_{spl,max}=R_{segment}-(n-1)*R_{spl,avg}$. All busbar segments, 8 dipole and 7 quadrupole ones, selected to be redone were found to contain at least one or more SC cable-to-cable joints with significant defects, like a lack of solder or overheated strands.

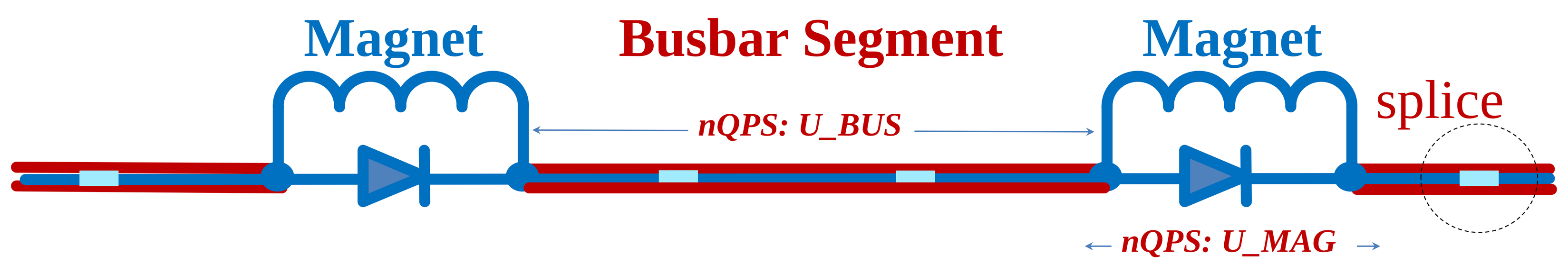


Deffective magnet splice: no solder between cables, nor between cable and copper.

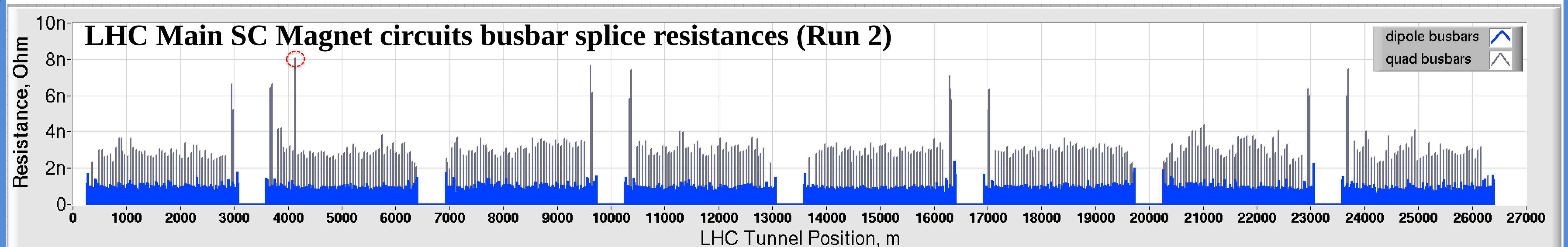
The analysis of a few hundred ramps allowed calculating the magnet resistances with about ±0.5-1.0 nΩ accuracy while the expected or nominal value is ~2.5 nΩ. 8 magnets with resistance higher than 15 nΩ were exchanged. In all opened magnets, the high resistance was confirmed by identifying a lack of solder in one of the internal superconducting cable splices.

nQPS, Splice Monitoring

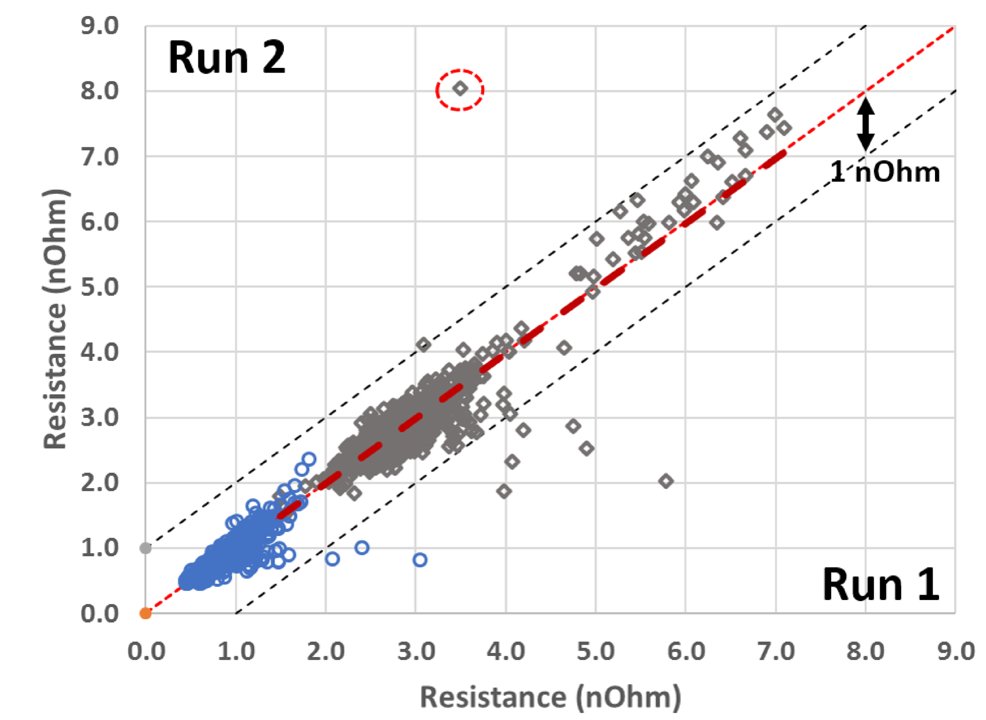


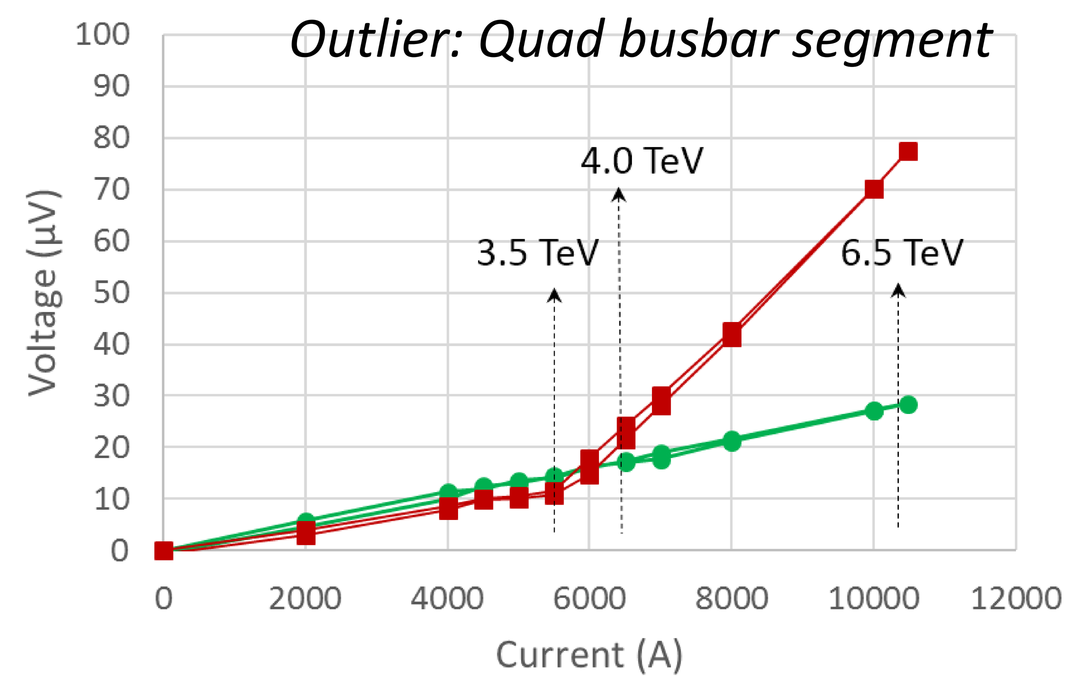


The resistance calculations are triggered every time the LHC operates about one hour at injection level and remains afterwards for more than one hour at actual top energy (Table II). The average busbar splice resistance can be calculated with about ±50 pΩ accuracy already from a single ramp, taking into account the splice number per segment. A Gaussian fit on the measured resistance data provides self-consistent results for two, respectively three splice segment resistance values and for the variance between them (Figure on the left|).



SMACC: Run 2 vs Run 1





The left figure present the busbar segment resistances (RB and RQ circuits), calculated from Run 2 data versus the same resistances from Run 1. The general conclusion one can make is that the splice resistance measurements at 1.9 K confirm once more the successful consolidation done by the SMACC-project during LS1. Despite more than 3000 out of 10306 splices that have been redone during the consolidation, the overall correlation plots show that all splice excess resistances remain within 0.5 nΩ for the dipole circuits (blue) and within 1 nΩ for the quad circuits (gray), with a single exception. The highest estimated busbar splice resistances, $R_{spl,max}$, reduced to 1.0±0.1 nΩ for the RB and 1.9±0.1 nΩ for RQ circuits following the LS1 consolidation.

The resistance of one of the quad circuit busbar segments was measured to a significantly higher value than other segments, about 8 nΩ. The special pyramidal powering test shows clearly the non-linear behavior of the busbar resistance when the circuit current is higher than about 5 kA (red curve). Taking into account the fact that the busbars were designed to safely handle a current up to 13 kA even in case of quench, the concerned busbar segment is considered safe for LHC operation at 6.5 TeV. Note the resistance of the busbar segment is continuously monitored since LS1 and did not show any farther signatures of degradation.