LHC BEAM ENERGY IN 2012

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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. The measurements performed in 2009 in the whole machine, in particular in sector 3-4 during the repair after the 2008 accident, demonstrated that there is a significant fraction of defective copper bus bar joints in the machine. In this paper, the limiting factors for operating the LHC at higher energies with defective 13 kA bus bar joints are briefly reviewed. The experience gained during the 2011 run, including the quench statistics and dedicated quench propagation tests impacting on maximum safe energy are presented. The impact of the by-pass diode contact resistance issue is also addressed. Finally, a proposal for running at the highest possible safe energy compatible with the pre-defined risk level is presented.

INTRODUCTION
The Large Hadron Collider (LHC) at CERN has made remarkable progress during the 2011 run, well exceeding its ambitious goal for the year in terms of integrated luminosity delivered to the LHC experiments. As in 2010, the operation with beam energies of 3.5TeV was pursued during the whole 2011 run. The first promising results of the analysis of the data acquired in 2011 and the first precursors to a discovery of the Higgs boson strived for further energy increase for the 2012 run.

The protection of the superconducting circuits of the LHC, i.e. magnets, bus-bars and current leads is ensured by electronic quench detection systems in combination with active protection elements such as quench heater discharge power supplies and energy extraction systems [1], [2]. The LHC superconducting magnets are well protected against the quench induced damage. The protection of superconducting bus bars and current leads relies on a sufficient cross-section of copper stabiliser, allowing the conduction of the current during the energy discharge in case of a bus-bar quench. As it is discussed in detail in several papers [3], [4], [5], the LHC interconnection joints of the main circuit bus bars do not have the required quality and are of major concern for running the LHC at higher energies.

The main dipole and quadrupole magnets in each of the eight sectors of the LHC are powered in series. Each main dipole circuit (RB) includes 154 magnets and 156 bus bar segments. The quadrupole circuits (RQ), depending on the sector, include either 47 or 51 magnets and 96 or 104 bus bar segments respectively. Both types of bus bars contain a single 15.1x1.5 mm² Nb-Ti Rutherford cable in the centre of the copper bar. The main difference between dipole and quadrupole bus bars is the total cross section which is 20x16 mm² for RB circuits and 20x10 mm² for RQ circuits [6]. The 10307 connections between the bus bars are soldered by inductive heating using Sn96Ag4 alloys. During this process the two superconducting cables are connected (spliced) with an overlap of 120 mm. The expected average splice resistance R_{sp} is about 0.3 nΩ at 1.9 K with an acceptance limit of 0.6 nΩ. 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.

In a good bus bar interconnection joint [3], the copper stabilizer in the joint together with the bus bar stabilizer on either side of the joint, should work as a continuous electrical shunt to the SC cables. This is achieved when the Sn96Ag4 solder fills all voids in and around the splice (see Fig. 1). Even if there is a correct splice resistance between SC cables, a 13 kA joint can burn-out, should there be a quench, due to a bad bonding between the SC cable and the copper bus, coinciding with a discontinuity in the copper stabilizer.

Significant lack of soldering material can result in both, a discontinuity in the copper stabilizer and a lack of SC cable bonding to copper. In such a situation, a quench in the splice can lead to a fast thermal runaway generated by the heating in the SC cable. In addition, the bad thermal and electrical contacts between the cable and copper stabilizer prevent efficient conduction of heat. In defective splices the current will not flow continuously through the splice stabilizer, but will be forced to flow in the SC cable, which in its normal conducting state exhibits significantly higher resistance than copper.

The proposal for the maximum safe beam energy in 2012 is given at the end of the paper and is based on the following inputs:
- the status of the copper joints and the SC splices,
- diminution of the multiple quench events,
- heat propagation in the quenched magnet towards the interconnect,
- excessive resistance in the by-pass diode leads.

These topics are discussed in the next sections of this paper.

Figure 1: Schematic view of a 13 kA splice with and without good solder filling.
STATUS OF THE INTERCONNECTION JOINTS RESISTANCES IN THE LHC MAIN MAGNET CIRCUITS

Status of the copper joints

The main input to the computation of the probability of a splice burnout is the resistance of the copper stabilizer joints in the machine. The estimation of the percentage of joints with an excess resistance above a critical value for given energy relies on a very limited set of 134 direct joints measurements (out of 10307 joints) performed in the machine in 2009 [7]. Our knowledge of the condition of the defective joints comes from a subsample of 23 joints, exhibiting excess joint resistances above 20 $\mu$Ohms. The analysis fits a functional form on the distribution of these 23 values and this functional form is used to estimate the number of joints exceeding a specific threshold, critical for a given maximum safe energy of the LHC. This analysis is in practice unchanged since 2009 [8].

Status of the SC cable splice resistances

The new layer of the enhanced magnet Quench Protection System (nQPS) consists of 436 electronic crates distributed along the LHC tunnel. By means of these crates, the resistance of every one of the 2048 main magnet bus bar segments is monitored. During the 2009-2010 LHC commissioning campaign [9] dedicated powering cycles, the so-called pyramids, were performed on all LHC main magnet circuits. The data sets were recorded with the nQPS system during current ramping up and down with 10-12 current steps. The current was kept constant during 10-20 min for each step. These measurements allowed to qualify the bus bars for each higher current level, evaluating the superconducting bus bar segment resistances with unprecedented resolution, better than 1n$\Omega$ in challenging signal to noise conditions.

Since March 2010, when the LHC was successfully restarted at 3.5TeV, the bus bar resistances are monitored during all long physics fills. The current plateaus are automatically detected, the nQPS records the voltage and the resistance is calculated. The resistance calculations are triggered if the LHC operates about one hour at injection level and stays afterwards for more than one hour at top energy. The bus-bar segment resistances $R_{\text{segment}}$ are calculated by a linear fit of $U(t)$ curves which are constructed from the acquired $U(t)$ and $I(t)$ time series taking into account only the plateau points. The current data $I(t)$ are provided by the controllers of the LHC power converters with an accuracy of about 2 ppm [13]. In total, the bus-bar resistances have been calculated from about 500 ramps of the LHC beam operation in 2010 and 2011.

Figure 2: The maximum splice resistances $R_{\text{spl,max}}$ versus tunnel position, where $R_{\text{spl,max}} = R_{\text{segment}} - (n-1)R_{\text{spl,avg}}$.

Figure 3: Gaussian fit of the dipole and quadrupole splice resistances.

Figure 4: LHC bus bar splice resistances at the end of 2011 versus the end of 2010.
electrical point of view 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 [10]. However, a high splice resistance might indicate a mechanical weakness of the joint due to an improper soldering process. Deterioration over time cannot be excluded, although the two years monitoring of the splice resistances from each high current plateau did not show any degradation of these splices so far (see Fig. 4).

**DIMINUTION OF MULTIPLE MAGNET QUENCH EVENTS**

One of the most important challenges for the magnet quench detection system is to cope with the electromagnetic transients and/or the high inductive and high resistive voltages caused by a fast power abort (FPA), involving switching off the power converter and activation of the energy extraction to the dump resistors [14]. The vulnerability of the LHC quench detection system to withstand the effects of a hostile environment and various transient signals produced by circuit elements caused a number of multiple magnet quench events in 2010. An example of a multiple dipole magnet quench observed on 11.3.2010 in sector 1-2 is shown in Fig. 5.

The electromagnetic transients can cause spurious triggers both in the initial and new QPS, resulting in a quench of a number of magnets. Initially, the power converter was switched off at the same time when the energy extraction resistors were switched into the circuit. To reduce the transient signals, a modification of the resistance in the passive filter at the output of the RB power converter was implemented and delays of the energy extraction at the even and the odd side of the sector were introduced with respect to switching off the power converter. At the same time, the snubber capacitors were installed in parallel to the switches to reduce the electrical arching and related transient voltage waves in the circuit (see Fig. 6).

In Fig. 7 the results of numerical simulations of transient voltages appearing during the FPA for three different configurations are shown. All three configurations were implemented and investigated in the machine, namely:

- Configuration 1: original configuration used before March 2011.
- Configuration 2: featuring a delay between the power-converter switching-off and the opening of the extraction switches,
- Configuration 3: featuring a delay between the power-converter switching-off and the opening of the extraction switches as well as the snubber capacitors in parallel to the extraction switches and additional resistance in the filter at the output of the power-converter.

**QUENCH PROPAGATION TESTS**

For each main dipole and quadrupole magnet, a diode is installed in parallel in order to bypass the current during the discharge in case of a magnet quench. During several technical stops in 2011, the resistances of the diode leads for six dipole magnets and for six quadrupole magnets
were measured. The results showed non-reproducible resistances much larger than expected 5 \( \mu \Omega \) (see Table 2).

Table 2: The dipole by-pass diode lead resistances measured in the machine.

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The performance of diodes observed in the machine was unexpected, but analysis of the data from the past has shown that similar behavior was already present during the reception tests of diodes. The recorded signals could not be explained by simple Joule heating in the resistive bus bars with constant contact resistances. The analysis indicates that most of the excess resistance must originate at the “diode - heat sink” contact (see Fig. 8). Thanks to the diode stack design the heat sink has a significant enthalpy margin, and relatively large excess resistances between the diode and the heat sink are acceptable, as long as there is sufficient thermal contact between these elements. In contrary, the bolted contacts of the diode leads are critical with respect to the contact resistances and must be carefully investigated. For this purpose a series of cold tests of well instrumented diode stacks was performed in cryogenic condition in SM18 test facility in order to give more insight into the behavior of the contacts. As a main result, the behaviour of diodes observed in the LHC tunnel has been confirmed as a typical one and, even if not yet fully explained, it is not considered as a critical issue for the LHC operation. The observed behaviour seems to be characteristic of the diode to heat sink contact at cryogenic condition and for intermediate current levels. Further tests are on-going in SM18. No massive intervention is planned on the diodes during LS1, however local tests and/or inspections are possible.

**MAXIMUM BEAM ENERGY FOR 2012**

*Update on burnout probability calculations*

The simulations presented during Chamonix’11, 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 are in principle still valid. The only new parameter, relevant for the burnout calculations is the new minimum RRR of the SC cable in the splice area. In previous simulations the minimum cable spec value of RRR=80 was assumed, confirmed by measurements on bare cables. This RRR value is affected by the inductive heating applied during the joint soldering process. The values measured on real joints in the FRESCA test facility allows an increase of the minimum RRR to 100, which is then used as a more realistic input for safe current simulations shown in Fig. 9 (solid line “Chamonix 2012”).

![Figure 8: The dipole by-pass diode stack and its elements.](image)

![Figure 9: Defective splice burn-out calculations including RRR = 100 for SC cable in the splice area.](image)
What has really changed since Chamonix’11?

In 2011 the number of spurious quenches was radically reduced. This was achieved mainly by improvements introduced to QPS after and thanks to much better simulations and understanding of transient effects in the main circuits. In 2011 only 1 single-magnet spurious quench (most probably due to SEU) was recorded. The number of observed spurious quenches is the most important difference between 2010 and 2011 and it impacts on both arguments that in Chamonix’11 lead to limit the energy to 3.5 TeV. The best proof of significant improvement with respect to the spurious quenching was the event of August 18th when a total power cut at LHC was experienced at the most critical for magnet circuit moment close to the top energy (see Fig. 10). No single magnet tripped. If such an event had occurred one year earlier, we would have experienced massive QPS trips around the ring.

Re-commissioning of the protection systems

The re-commissioning campaign will profit from the experience gained so far. Additional tests will be required during the powering tests in order to qualify some newly installed upgrades of the quench detection and energy extraction systems, as well as qualification of all magnet circuits to the 4 TeV top energy level.

Maximum safe beam energy

During the Chamonix’11 we were at the “edge” regarding the decision about the 4 TeV/beam operations with 52 s energy extraction time constant. The decision to not operate LHC at 4 TeV/beam was difficult, in particular because no showstoppers from equipment point of view were identified. Main arguments against 4 TeV were:

- number of spurious quenches observed over 2010, in particular several events involving large number of dipoles,
- no experience with quench sensitivity to beam losses for beams with high energies (of the order of 100 MJ),
- very small margin for nQPS (symmetric quench detectors) at 4 TeV with $\tau = 52$ s. In case of simultaneous quench of 15 dipoles the nQPS symmetric quench detectors are saturating and are blind.

In 2011 the number of spurious quenches was radically reduced. No single beam induced quench was observed and during the whole year of operation only 1 high current, single magnet spurious quench with beams was experienced, most probably due to the SEU. This was achieved mainly thanks to the snubber capacitors installation and improvements introduced to the power converters and energy extraction delays.

The risk factor is the product of probability and impact. The probability of a splice burnout at 4 TeV/beam in 2012 is for sure not higher than the probability which had been estimated in 2011 for 3.5 TeV/beam, but it is important to remember that the number of spurious quenches must be kept low. In particular, the events involving a large number of quenching dipoles must be avoided.

SUMMARY

There is some new information and measurements that were performed in 2011:

- during LHC operation in 2011 it was demonstrated that the risk for multiple dipole quenches due to electromagnetic coupling is greatly reduced by the installation of snubber capacitors, modification of the power converter passive filters, and modifications of the energy extraction,
- the parameter, crucial for the burnout calculations, which is the minimum RRR of the SC cable in the splice area, is higher than originally anticipated. In previous simulations the minimum cable spec value of RRR=80 was assumed, whereas due to the inductive heating applied during the joint soldering process the RRR is increased to about 100.

In addition:

- the assumption that all measured copper joint excess resistance is concentrated at a single splice on its one side is considered as very pessimistic,
- the measured anomalous resistances of the diode leads has been localized near the heat sinks and due to the heat sink heat enthalpy margin are not critical,
- there was not a single beam induced quench with circulating beams in 2011.

Operational experience with beams exceeding 100 MJ demonstrated that the BLM thresholds are efficient to dump the beams before the beam losses exceed the quench level. In particular, the total power cut on 18 August 2011 on the ramp near maximum magnet current with high beam intensity, did not result in a single quench. This confirms that the systems are working very well, the beams are dumped in time without risking...
quenching the magnets and that electromagnetic coupling is no longer a serious concern.

The risk factor is the product of probability and impact. The probability of a splice burnout at 4 TeV/beam in 2012 is not higher than the probability which had been estimated in 2011 for 3.5 TeV/beam. With the improvements made in 2009 (installing additional small Helium release valves in all sectors, and larger valves in more than half the LHC) the impact of any splice damage would now also be lower than in 2008 by about a factor of two [11] and also by another factor of two due to reduction of the decay time constants during the energy extraction.

REFERENCES