PRECONDITIONS FOR OPERATING AT 5TEV IN 2010

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Abstract

The magnet powering system of the LHC has been commissioned in 2009 to the 1.2TeV equivalent to allow for initial beam operation and first collisions during November and December 2009. As part of this Hardware Commissioning campaign, a huge effort has been undertaken to increase the knowledge on the status of the interconnection splices through at warm and cold measurements. The results and lessons learnt with the different equipment system and the enhanced QPS system are summarized and an outlook is given on the necessary consolidation and additional commissioning which will have to be done to safely reach higher energies and intensities in 2010.

INTRODUCTION

During the second half of 2009 and following the repair and consolidation of the LHC after the 2008 incident, the LHC magnet powering system has been fully re-commissioned in 2009. While the main magnets were only commissioned to 2kA for the initial months of operation, they are currently being commissioned to reach 6kA, allowing for operation at 3.5TeV in 2010. This requires for a first time the extended QPS system to be fully operational to protect the magnet interconnection splices, which have been measured using this system for the first time with great accuracy in the whole machine.

Similar to the beam energy (and magnet current), the beam intensity was kept very low for first operation in 2009, which allowed however gaining very valuable experience with first beam commissioning while still operating with safe beams.

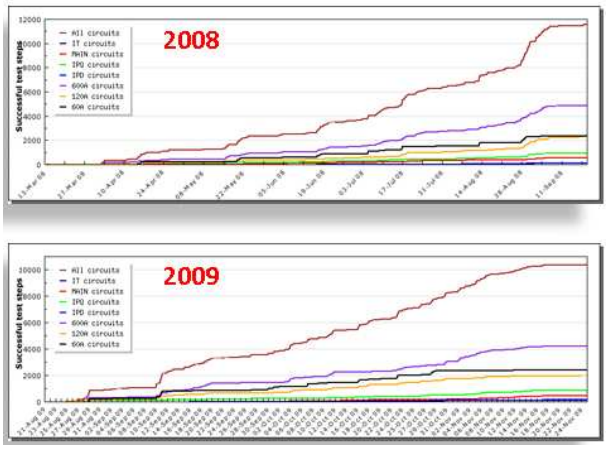

Figure 1: HWC in 2008 and 2009

As for the magnet protection system this flexibility will be lost for other equipment and machine protection systems when moving to higher energies and intensities, therefore it is of vital importance to fully understand and apply the lessons learnt during initial operation end of 2009.

HWC IN 2009 AND BEYOND

Despite the increased complexity of the protection systems following the introduction of the nQPS system, the Hardware Commissioning campaign in 2009 went very smooth, and the overall time could be reduced by almost 50% as shown in Figure 1 (keeping in mind that the main circuits have only been commissioned to the 1.2TeV equivalent for initial beam operation).

This increased efficiency was mainly a result of increased parallel commissioning (up to 5 sectors in parallel) and increased automation of the performed tests and their analysis.

Efficiency can however be further increased in several areas to achieve a re-commissioning of the whole machine in 4-5 weeks during future campaigns. Preparations for future hardware commissioning should be started soon in order to update the commissioning procedure and to allow for the timely definition and implementation of further improved tools.

INTERCONNECTION SPLICES

The current knowledge of the interconnection splices is of primary importance in order to determine the energy at which the machine can be operated safely prior to the upcoming consolidation program (aiming at mitigating splice defects as they have been observed in the machine and which are illustrated in Figure 2). Large efforts have therefore been undertaken during the HWC campaign in 2009 to measure the splice resistances, both at warm and at cold.

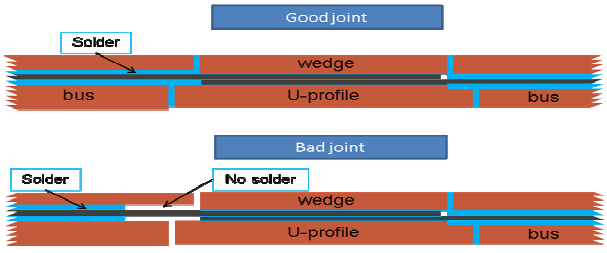

Figure 2: Interconnection splices with and without defects

Splices at cold (i.e. in the superconducting state) have been measured in the whole machine with great accuracy and did not show any excess resistance above 4nΩ. An excess resistance above 2nΩ does not pose any problems under normal operation but might suggest a structural problem or a problem with the soldering procedure and their evolution over time should thus be observed closely.

Splices at warm (i.e. measurements of the continuity of the copper stabilizer) have been measured everywhere but in sectors 78 and 81 and extrapolated using statistical methods to the whole machine. While the worst measured splice shows a resistance of 60μΩ, this extrapolation leads to the assumption of a 'worst case splice' of around 90 μΩ existing in the machine.

Based on the calculations of A.Verweij (revealing a value of 80μΩ as the worst acceptable splice resistance for safe operation at 3.5TeV) the current knowledge of the interconnection splices leaves no margin for operation at 3.5TeV and running at 5TeV is not recommended without major repairs after a warm up. Additional methods have been proposed which would allow to further increase the knowledge of the interconnect splices, a low current method that can measure the RRR of the busbars and a high current method (the Thermal Amplifier) which is sensitive to the worst splices in all bus bar segments.

ENHANCED QPS SYSTEM

To assure the protection of the interconnection splices, additional electronics and the related cabling has been installed during early 2009 and addition steps for its validation have been included in the commissioning program. This nQPS system represents an increase of around 1/3 with respect to the existing system and consists of around 440 additional crates, 4000 detection boards and 900 power packs, interconnected with more than 240 km of additional cables and 7800 connectors. With this system the voltage across interconnections of LHC main magnets is permanently monitored and interlocked at 300μV/10s for nominal operation at 12kA (for 3.5TeV a threshold of 500μV, 10s is sufficient). In addition aperture symmetric quenches can be detected which will become an essential functionality for magnet training up to nominal current. The symmetric quench detection system serves as well as back-up for the existing system to detect also 'normal' quenches.

During the hardware commissioning campaign the nQPS design has been successfully validated and commissioned in passive mode (i.e. not yet connected to the interlocks and quench heaters) up to a current of 2kA. After verification of the signal integrity and compensation adjustments at these moderate currents the nQPS system is connected into the interlock chain before proceeding the commissioning with higher current values. The new hardware allowed as well to establish for the first time the complete mapping of all superconducting interconnection splices for the 24 main circuits (as shown for the main quadrupole circuits of sector 12 in Figure 3). Despite the moderate current of 2kA the obtained resolution of ~400pΩ allowed to confirm the conformity of all superconducting splices after the recent consolidation program.

While most sectors where operated in 2009 still without the nQPS connected, sector 12 was already fully activated and allowed gaining first encouraging operational experience. The system proofed to be reasonably stable with the exception of a few EMC problems which were observed in the sector (originating in the pulsing of the nearby transfer line magnets).

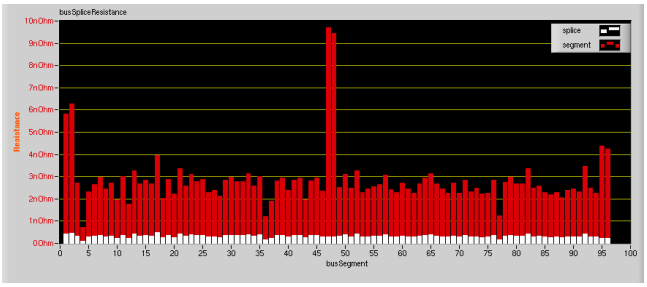

Figure 3: Splice mapping for main quadrupole circuits RQD/F.A12 as obtained end of September 2009

In order to reach energies beyond the 3.5TeV range no major additional commissioning is needed for the QPS system apart from the installation of additional 'snubber' capacitors on the energy extraction systems. A further extension of the nQPS system to the individually powered quadrupole/dipoles and inner triplet circuits is currently being prepared and a potential problem related to the radiation weakness of the latest version of the field-bus chip is being addressed [1].

HOW TO SAFELY REACH HIGHER INTENSITIES AND ENERGIES

The LHC Machine Protection System has been commissioned in 2009 for low intensity and low energy beam operation. During this period interlocks were activated step by step and masking of channels was one of the means used to improve the commissioning efficiency by allowing for the needed flexibility. Still a large majority of the interlocks were already tested and activated, without contributing in a significant way to the downtime of the machine. A few more tricky issues remain to be resolved for 2010 related to the reliability of some safe machine parameter flags and 'cross-talk' shower signals and saturation issues of BLMs at over-injection.

Beams where however very modest (the stored energy did not exceed 30kJ) and as intensity and energy are increased this flexibility will be lost as the machine has to be protected at all times. It is therefore essential that all protection functionality is commissioned beforehand at low intensity. Intensity and energy must then be increased progressively, and every new step in energy or optics must be performed at low intensity.

In order to safely reach the targets for 2010 (with stored beam energies starting to exceed the MJ range) , the machine will require a very careful setup for unsafe beams, a well established operational cycle, good diagnostics and a reliable control system.

Machine Development phases interleaved with standard operation are a potential threat and should be limited to the absolute minimum as settings might be changed and interlocks masked without being restored at the end of the MDs.

EARLY BEAM OPERATION OF THE BEAM LOSS MONITORS

The beam loss monitors (BLMs) have shown a very satisfactory performance, whereas it has to be noted that only very few monitors where actually connected into the Beam Interlock System at the beginning of the 2009 run. At the end of the run the LHC was though operating with most of the channels unmasked. The passage to unsafe beams will be an important step for the BLMs as it will require reaching the full protection level and the validation of the applied thresholds. The noise and offset on the monitors is hereby a very important factor determining the availability of the system (i.e. the number of false dumps). An effort to exchange long cables has allowed to reduce the noise by a factor of 2 on these monitors already, future installations of single pair shielded cables will further improve this by a factor of 5 (during a future shut-down only). Secondary Emission Monitors have hereby shown a higher percentage of large noise than Ionization chambers (detailed cause of this effect is currently under investigation).

Until now only four quenches have been observed (all on main dipole magnets) which all occurred right after injection of the beam but which already allowed validating the accuracy of the related thresholds levels (see Figure 4). However, the MB magnets are typically not protected by BLM. All other magnet types (which are protected by BLM) need dedicated beam test to validate the thresholds. Also, the steady state loss thresholds need dedicated beam tests. Full application of the BLM system tests and system change procedures will be enforced. A few known BLM system limitations persist but they look compatible with the current LHC schedule (i.e. higher thresholds on some warm elements which are limited by the dynamic range and higher thresholds for TDI and triplet regions). No additional limitations have been found for energies up to 5TeV. The collimation cleaning looks already very promising, the injection losses observed during the 2009 run were however very high and need to be substantially reduced for 2010.

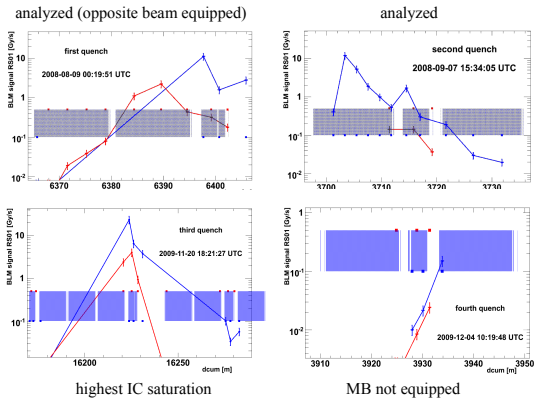

Figure 4: Analysis of BLM signals for the four magnet quenches of main dipole magnets after beam injection

Additional Beam tests have been proposed at the beginning of the 2010 run in order to determine safe settings of threshold values.

WHAT ELSE NEEDS TO BE DONE TO REACH 5 TEV AND BEYOND

Apart from additional commission steps for the LHC magnet powering and machine protection systems, a number of consolidation activities have to be performed before the energy can be increased to 5TeV. The values of the energy extraction resistors for the main dipole and quadrupole circuits which have been increased for the 3.5TeV runs will have to be decreased again to avoid exceeding the voltage ratings of other elements in the electrical circuit and overheating of the dump resistors. Additional snubber capacitors will have to be installed to reduce the amplitude of the voltage wave which might inhibit the extinction of the arc during the opening of the energy extraction switches.

Several magnet non-conformities will have to be revisited, e.g. the MCBYHS5.R8B1 [2] and MCBXH/V magnets are required to generate the crossing angle and the present non-conformities introduce an additional constraint on the possible physics scheme.

The vacuum leak in the middle of the arc 34 still persists (with ~ 2mbar l s^{-1}) but thanks to two additional turbo pumps this is deemed acceptable for operation in 2010. Additional consolidation of the gas flow control valves should be foreseen as they might impact the overall reliability of the cryogenic system.

CONCLUSION

During the 2009 HWC campaign the LHC magnet powering system has been commissioned to the 1.2TeV equivalent to allow for initial beam operation. Large efforts have been undertaken to increase the knowledge of the interconnection splices in order to determine 3.5TeV as the energy at which the machine can be operated safely prior to a large scale consolidation program. Prior to operation at 3.5TeV the nQPS system will have to be commissioned to the equivalent current of 6kA in the main circuits and a large number of machine protection tests will have to be completed at low beam intensity before increasing the intensity above the safe limit. Apart from the well defined test program, only a very careful setup for unsafe beams, a well established operational cycle, good diagnostics and a reliable control system will allow to safely reach the targets for 2010 with beam energies exceeding the MJ range.

REFERENCES

[1] J.Serrano: Chamonix 2010, Session 6 - Radiation to Electronics, **"**Is the WorldFIP a reliable Rad-hard Fieldbus on long term?", these proceedings

[2] Y.Thyrel et al. : "Analysis of the RCBYHS5.R8B1 circuit", EDMS Doc Nr. 105397