REVIEW PANEL REPORT
HL-LHC Magnet Circuits Internal Review

Internal Review Date: 2017-03-17	***Project/Activity: HL-LHC***

Review Panel Members: Luca Bottura, Lucio Rossi (Chair), Rudiger Schmidt, Andrzej Siemko, Thomas Taylor, Davide Tommasini and Akira Yamamoto.

Scientific Secretary: Felix Rodriguez Mateos.

1. Introduction

The High Luminosity LHC (HL-LHC) Project requires a considerable upgrade or modification of the insertion region magnets of insertions IR1 and IR5 of the LHC and the introduction of two 11T cryo-assemblies at the dispersion suppression region at point 7.

After months of work together with the relevant work packages at the Magnet Circuit Forum (first meeting July 2016, 13 meetings until now, plus some other topical meetings), some points remain open at a conceptual level. It has been considered wise to call for an internal review in order to close them by taking appropriate decisions. The review is hence organized in a focal way, i.e. to answer questions to those open points. The review remains at a conceptual level as technical developments of hardware fall in the domain of the reviewing process that each work package will follow in the course of this year and beginning of next one.

The review panel (members given in Appendix 1) was charged to examine the choices presented at the review meeting (agenda given in Appendix 2) in the light of finalizing the circuits on a conceptual level and to advice on a roadmap to close the open issues. The review was divided in three main topics related to the open issues:

- 11 Tesla Dipole Circuit
- Matching Section Circuits
- Inner Triplet Main Circuit

The questions that are proposed to be answered by the internal review panel were the following:

General Overview

- Is the level of detail presented on the circuits enough to complete a baseline at a conceptual level?
- Do you see any issue that should have been discussed that was not sufficiently examined?
- Do you think the follow up given with respect to the coordination of circuits is the correct one? Do you have any advice?

11 Tesla Dipole

- Is the trim circuit required for the 11 Tesla Dipole? Are the arguments for the “yes” or “no” sufficiently clarified?
- In case the trim is required, which option would be the most suitable for the crowbar resistance for the 11 Tesla Dipole?
- Are the quench protection conceptual details on the 11T dipole well defined?

- Are the powering conceptual details of the 11T Dipole well defined?
- Are the electrical quality assurance test levels well defined and built on solid grounds?
- Are there any other aspects that may require follow-up in your opinion?

Matching Section

- Are the minimum requirements in terms of correctors properly justified?
- Would you recommend reducing the number of corrector circuits by connecting MCBY magnets in series in Q4 and/or Q5? If so, are the implications for having a reduction in the number of corrector circuits well balanced in terms of pros-cons?
- Do you agree with the proposed strategy of reusing the DSL for the powering of the corrector circuits together with local powering? Do you see any showstoppers to this strategy?
- Have the pros-cons related to the requirements in order to preserve the possibility of installing MQYYs and the 600 A correctors during LS4 and LS5 sufficiently explained? What is your recommendation in this respect?
- Are there any other aspects that may require follow-up in your opinion?

Inner Triplet Main Circuit

- Is the 120 A trim required for the HL-LHC operation? Or could it be removed? Are the arguments for the “yes” or “no” sufficiently clarified?
- What are the main implications of the new proposed trim on Q1? Would it be really needed? Are the arguments for the “yes” or “no” sufficiently clarified?
- Are the quench protection conceptual details well defined for the Inner Triplet (QXF) circuit?
- Are the powering conceptual details of the Inner Triplet (QXF) circuit well defined?
- Does one need to limit the currents in order to preserve the present superconducting link ratings? Are cold diodes required? Advisable? But can cold diodes be installed in such those expected high radiation areas?
- Do you think quenching of the link is acceptable in the presented conservative scenario?
- Does one need to upgrade the link ratings to avoid quenches? What are the implications?
- Are the electrical quality assurance test levels well defined and built on solid grounds?
- Are there any other aspects that may require follow-up in your opinion?

2. Review Panel Report

2.1. General Overview

It is first noticed that the “internal” character of the review is important, since it is a milestone in the reflection on the design and on the choice optimization. The presence of experts and GLs is also to assure the HL-LHC management that the consequence or suggestions can be followed up by the respective groups, and has assured a dynamic discussion.

As a result of the review, a lot of simulation work has led to a better understanding of the currents that can be expected to flow in various parts of the inner triplet circuit in fault conditions. In the meantime, the possibility of adding cold diodes to reduce associated risks was proposed and discussed at the present review.

With regard to the 11T Nb_3Sn magnet it is confirmed the baseline of equipping it with a 250 A trim power converter to enable compensation of differences in the transfer function between the 11T dipole and the regular Nb-Ti LHC dipoles. This will entail the design of local current leads to be integrated on the cryostated cold mass.

For the matching section, the proposed modifications are appropriate if the DSL doesn't have to be removed for the installation of the QRX. Otherwise it would probably be advantageous to replace the system. It is therefore urgent to determine whether or not the DSL has to be fully dismantled.

Following extensive simulation studies, the quench protection system proposed for the inner triplet string inspires a guarded increase in confidence. It is noted, however, that the estimate of peak current foreseen to circulate in the so-called trim cables increased from 2.5 kA to 4.5 kA between the International Circuit Review in February 2016 and a meeting in November 2016, and that very recent simulations now indicate that in – improbable – extreme adverse conditions up to 6.7 kA could occur. It is therefore recommended to change the inner triplet powering baseline in order to accommodate a request for increased ratings of some of the cables in the superconducting link. This implies a rearrangement of the cables within its cross-section. The question remains on how much contingency needs to be included.

New information on the characteristics of the proposed crowbars was welcomed as improving the operational functionality of the inner triplet powering system.

For the inner triplet, it is recommended that appropriate attention be paid to the Nb-Ti bus-work connecting the magnets within the cryostats, and to the routing of the copper bus-work and feedthroughs required for the CLIQ powering. However, the precise definition of this bus-work cannot be fixed until the full circuit is settled.

It was pointed out during the meeting that if the series operation of the magnets can be fully validated, alternative arrangements of power converters could lead to further significant cost savings and possible simplification of the overall system.

To conclude, on the basis of current information the series connection of the inner triplet quadrupoles and the present QPS strategy are fully validated. However, further optimization is still possible and should be studied. The possibility of inserting cold diodes, if proper validation is carried out on time and their integration properly studied , should be kept open as long as possible (but not too long to cause delay in the construction of components).

2.2. 11 Tesla Dipole Circuit

The presented baseline circuit design is to operate the new Nb3Sn 11 T dipoles in series with the main bending magnets. Compensation is inevitably required to balance the different magnetic characteristics through the use of either orbit correctors or a local trim PC. If used to include the correction scheme means that these orbit correctors could possibly become critical for machine operation even if the 11 T dipole transfer function is optimized.

The panel comments that the 11T dipole introduction should impact minimally the machine operation and should not add critical elements. The trim PC provides a viable complement to the aforementioned orbit correctors, but it does not simplify operation because all the correctors must be powered in any case. It does, however, reduce the load on the correctors and adds a degree of redundancy. The panel therefore recommends keeping the trim circuit in the baseline.

The panel comments that a high trim crowbar resistance is required to limit the currents to 250 A in the trim in case of powering abort. It is recommended that 250 A should be the nominal design value for the trim current leads.

The panel remarks that the impact of the trim PC on the QDS in case of powering abort on the 11T and neighbouring MB magnets must be further investigated by simulations and if possible by tests in SM18. These tests should be prepared and the associated hardware requirements assessed.

Concerning the impact of the flux jumps on the quench detection system, the panel supports the proposal to test the full-length prototypes in order to elaborate a suitable quench detection strategy.

The panel recommends to qualify the current leads by applying the same criteria for the voltage withstand levels as it is done with the similar elements in the circuit. The existing LHC conduction cooled current leads do not satisfy these criteria. A solution of conduction-cooled leads is much preferred to one based on gas cooling.

The panel endorses the fact that the trim power converter and the warm circuit should follow the 2 x (Worst Case Voltage) + 500 V design rule (2 x Full Energy Extraction Voltage + 500 V, therefore around 2.3 kV).

2.3. Matching Section

The present baseline consists in maximizing the use of the current DSL and DFBL to feed the HL-LHC's Q4, Q5, Q6 and correctors magnets. No issue is foreseen for Q4, Q5 and Q6 magnets since they have the same current rating as for the present LHC magnets. Concerning the correctors, 8 MCBY correctors for Q4 (+2 correctors with respect to present LHC), 6 MCBY correctors for Q5 (+4 correctors with respect to present LHC) and 2 MCBC correctors for Q6 (no change with respect to present LHC) are necessary for the operational requirements of the HL-LHC.

The panel recommends that the correctors be powered individually by providing local powering for the missing leads in Q5. The panel also recommends that a connection in series for four Q4 corrector magnets (2 circuits with two magnets each) be adopted in order to reduce the leads from 16 to 12 and hence eliminate the local powering in this magnet. This will require the addition of voltage taps and the necessary circuitry to fire the crowbar in the event of a quench.

The panel notes that the current design of the DSL and DFBL cannot fully accommodate the change from MQY/MCBY to MQYY/MCBYY for Q4, as it would not be practical to modify the DFBL. For a future replacement of the magnet during LS4 or LS5, the panel recommends that the upgrade package of the magnet should include the redesign of the feedbox system (either a completely new feedbox or addition of a small feedbox connected via a link). This aspect should be addressed at a later stage of development of the new magnet, and not impact on work for HL-LHC during LS2 and LS3.

It was brought up in the review that the DSL might need to be dismantled in order to perform changes on the QRL. The panel recommends that in case of a dismantling of the DSL, the corrector SC cables should be kept at a rating of 600 A to include a possible change from MCBY correctors to MCBYY correctors. If dismantling is required, it might be wise for technical or financial reasons that the DSL be replaced to match the actual requirements, rather than to add extension pieces and multiple splices. The relevant groups (TE-MSC, TE-CRG) should launch a task force effort in order to agree on the requirements and the procedure for the dismantling and the reassembly of the DSL. A report should be prepared and presented to TCC for endorsement.

2.4. Inner Triplet

The present baseline design consists of one main power converter of 18 kA rating, 2 trim power converters of 2 kA rating and 1 trim power converter of 120 A rating. The presented baseline quench protection scheme includes outer layer quench heaters with inner layer quench heaters and/or CLIQ, the two last systems providing redundancy in case of failure. However, only one between IQH and CLIQ is needed, the decision is to be taken after the test of the first long prototype.

Following a report that magnet sorting would be sufficient to provide full functionality, the panel recommends the removal of the Q2a 120 A trim power converter from the baseline. The need for local K-modulation will, however, require an additional small trim of about 30 A for Q1.

The panel considers that the presented powering circuit is a robust solution, provided the 2 kA and 120 A SC trim cables in the superconducting link can be upgraded to a rating of about 5-6 kA (to avoid quenching of the SC link in almost all cases of a magnet quench, an event considered rare and estimated in once a year) and 5 MIITS (to provide safety against any event of quench). It was, however, noted that this rating is higher than the 2.5 kA at the 2016 International Circuit Review, and the 4.4 kA of last November. The worst possible case at ultimate current gives a peak of 6.7 kA in a "trim" SC link cable. Hence, changes are required to the present link cable cross-section. In the discussion, a few members of the panel suggested to reconsider the need for spare 18 kA cables within the link. This suggestion may mitigate possible issues (if any) due to the increase of size of the trim cable within the link envelope. Thanks to the dynamic reaction to the changing (but converging) boundary conditions, the panel endorses the adoption of a new baseline with the above-mentioned modifications: one can be confident in the simulations, but experience with magnet testing is sparse, making it difficult to benchmark. The team is therefore encouraged to complete the optimization over the next few months, integrating information from magnet testing. The panel reiterates the importance of the string test for comprehensive validation.

It was stated that the quench detection will have less time margin than in LHC, but one that is nevertheless considered to be reasonable by the specialists. The quench protection systems for HL-LHC will be based on the LHC QPS, which has proven reliability, and the panel is confident that it will be effective. However, because of the short margins on the timing it is recommended to perform a reliability study and time delay study on the QPS for the HL-LHC circuits in general and the IT main circuit in particular.

The panel is strongly in favour of the crowbar of 30 V proposed (possibly 50 V) for the main power converter that reduces the current ramp down time from 1750 s to less than 500 s (from ultimate current). This will allow for a moderately fast ramp-down without quenching the magnets, in the case of slowly evolving problems (e.g. with cryogenics). The original strategy, to quench all inner triplet magnets simultaneously should any SC component of the circuit quench, remains the cornerstone of the QPS.

While endorsing the present solution with the above-mentioned modifications, the panel recommends continuing studies on a possible further optimization for the circuit operation. An example is the introduction of cold diodes. The panel recommends to develop and test diodes capable of conducting up to 18 kA (time constant to be studied) and which are qualified for the expected radiation levels and liquid helium operation. In the future, such diodes may also be required at some locations in the main ring, so the panel recommends that a corresponding study be launched. The design and routing of associated bus-work in the cryostats and nearby feedbox should be undertaken to allow for their installation at a later date; this will nevertheless have an impact on the layout and integration.

However, it was pointed out that validation of the diodes for use in the expected environment could take many years, may be exceeding the deadline for revising the baseline. The cold powering system should be designed to work without the diodes, which, when (if) they come, will increase redundancy and reduction of risk (for example by reducing the sensitivity to different delays in firing the quench heaters and the CLIQ among various magnets).

The panel considered also the alternative, to connect the D1 magnet to the IT main circuit using a three-cable configuration. It was suggested that a study be made on the application of this topology as a possible mitigation strategy in case of a problem in an 18 kA conductor. A scheme for powering the IT and D1 with a single 13 kA PC, supplemented with a nested 4 kA PC, was also briefly discussed. This would feature the replacement of the 18 kA PC with (2-quadrant) 13 kA and could lead to significant simplification and cost reduction of the full system, carrying to a logical conclusion the series connection of the magnets. Validation would, however, require a further comprehensive set of simulations and benchmarking before considering a baseline change and this would take several months.

The panel recommends that WP3 devote appropriate attention to the design and integration of the bus-bars in the inner triplet circuits and the cables and feedthroughs for CLIQ. Special attention should be devoted to design and implementation of interconnects and splices.

Given the crucial importance of simulation work of the inner triplet main circuit, the panel strongly recommends to reinforce the team designated to take responsibility for the required studies, including benchmarking.

2.5. Provision for Rapid Disconnection of Cables for ElQA tests

It was mentioned that the ElQA team request that switches or similar quick disconnect equipment be installed between the power converters and the current leads, to facilitate the relevant high voltage testing at the end of shutdowns. Such equipment is quite cumbersome, especially for the 13 and 18 kA circuits, and it would be inconvenient to install it directly at the current lead or power converter terminals of the warm busbars/cables joining the two. They will therefore have to be located somewhere in between (preferably close to the current leads due to leakage current limitations to preserve the sensitivity of the ElQA measurements), and space allocated for their installation.

Acknowledgements

The panel wishes to thank all the speakers for their availability, clear inputs and big efforts. Some speakers have been asked further computing and discussion during a few weeks after the review day in order to arrive to the above conclusion (A. Ballarino, F. Menendez, R. Ravaioli, S. Yammine): to them our grateful thanks.

References

URL for the HL-LHC magnet circuit internal review: https://indico.cern.ch/event/611018/

Appendices

Appendix 1

Review Panel Members:

Luca Bottura (CERN), Lucio Rossi (CERN, Chair), Andrzej Siemko (CERN), Rudiger Schmidt (CERN), Thomas Taylor (CERN), Davide Tommasini (CERN), Akira Yamamoto (CERN and KEK)

Scientific Secretary:

Felix Rodriguez Mateos (CERN)

Administrative Secretary:

Celine Le Bon (CERN)

Appendix 2

The review meeting was held on 17/03/2017 at CERN in the Kjell Johnsen Auditorium (30-7-018) with the following agenda:

Time	Subject	Speaker
8:30-8:35	Introduction	L. Rossi
8:35-9:20	General overview	F. Rodriguez Mateos
11 Tesla Dipole		
9:20-9:35	Do we need the trim circuit?	M. Giovannozzi
9:35-10:05	11T dipole circuit considerations	S. Yammine
Matching Section		
10:30-10:45	Minimum need of correctors in the MS	R. De Maria
10:45-11:15	Optimized use of the existing DSL and local powering integration	V. Parma
11:15-11:35	MCBY correctors connected in series in Q5 (and Q4?): powering and protection	A. Verweij
11:35-11:50	What is required to preserve the possibility for powering the 600A MQYY correctors after LS4 or LS5? (cold powering)	A. Ballarino
11:50-12:05	What is required to preserve the possibility for installation of MQYY + 600A correctors during LS4 or LS5? (warm powering)	J.P. Burnet
Inner Triplet		
13:30-15:00	Minimum trim requirements and advantages of the single-circuit configuration	J.M. Coello De Portugal
13:45-14:15	IT circuit layout and optimisation	F. Rodriguez Mateos
14:15-14:45	Performance reach of cold powering beyond nominal conditions	A. Ballarino
14:45-15:00	Performance reach of warm powering beyond nominal conditions	S. Yammine
15:30-17:00	**Closed Session of the Panel**	