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Report from the Review Panel
for the
Conceptual Design Review of the HL-LHC Magnet Circuits

21-23 March, 2016, CERN Geneva

Review Panel Members
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1. Introduction

The High Luminosity LHC (HL-LHC) Project requires a considerable upgrade or modification of the insertion region magnets of the High Luminosity insertions IR1 and IR5 of the LHC.

The higher peak field, higher current and larger stored magnetic energy, as well as the necessity to relocate power converters (PCs) and sensitive electronics far from radiation areas, makes the powering system more complex and technically very challenging. "Mr. HL-LHC Circuit", Felix Rodriguez Mateos, has been appointed to ensure the consistency of the powering and protection aspects of the HL-LHC magnet circuits and steer the optimization of the overall system.

The review panel was charged to examine the baseline choices and possible variants with respect to the following aspects:

- Circuit Topology
- Magnet and Circuit Protection
- Circuit Integration
- Operation
- Voltage Withstand Levels
- Plan and Schedule

The review panel (members given in Appendix 1) was asked to review the conceptual "design" of the HL-LHC magnet circuits presented at the review meeting (agenda given in Appendix 2), and to advise/recommend "a new baseline" for the circuit system design to be prioritized for further design studies and demonstration/realization plans. The review was not asked to cover R&D works and/or the production program.

2. Report from the Review Panel

2.1. Executive Summary

The review panel members, have been impressed with the amount of work performed so far, leading to the presented thoughtful design studies for the HL-LHC magnet circuits and their protection systems to be as efficient and reliable as possible.

Based on the presentations given, a slightly different categorization has been applied to evaluate the conceptual design of each magnet system, each featuring a number of particularities. Therefore, we report the review results for each magnet system followed by common technologies, as follows:

- 11 T Dipole circuit and protection
- Inner triplet circuit and protection
- D1 and D2 circuit and protection
- Common Technologies

We generally support the conceptual design of the magnet circuit and related protection proposed in the baseline design or in the new baseline proposal presented during the review meeting, as follows:

- 11 T dipoles at the LHC arc section to be operated in series with the arc main bending magnets with the protection of the 11 T dipoles relying on redundant Quench Protection Heater (QPHT) systems,
- Inner triplet quadrupoles to be operated with a single two-quadrant power converter (PC) as the main PC and with 3 trim-PCs, with the protection of the inner triplet relying on a combination of QPHT and CLIQ systems to guarantee a maximum of redundancy and reliability
- D1-D2 dipoles to be operated with two independent PCs protected by redundant QPHT systems.
- Comments on the common technologies are reported in detail, in the following sections.

We strongly support the string test as being essential to demonstrate that the whole system can be reliably operated in nominal conditions and be protected for all possible failure modes.

The presented schedule is tight, and further studies will be inevitably required to allocate the necessary human resources and financial support to allow for the successful completion of the String test and the final installation of the project during LS3.

2.2. 11 T Dipole circuit and protection

Circuit

The presented baseline circuit design is to operate the new Nb_3Sn 11 T dipoles in series with the main bending magnets. Compensation is inevitably required to compensate for the different magnetic characteristics through the use of orbit correctors or a trim-PC.

We comment that the operational modes with either a trim-PC or orbit correctors should be further investigated, including possible failure modes. A trim-PC introduces a parallel circuit path and may introduce some risk for the main dipole circuit. The option of global orbit correction together with the optimization of the transfer function of the 11 T dipole should therefore be investigated in detail.

We recommend to provide current leads for a trim-PC in case it cannot be demonstrated with certitude that trim-PC are not required.

Protection

The presented baseline protection design foresees a combination of QPHT and parallel diodes. CLIQ application is not considered for the protection of the 11 T dipole. It is proposed to use variable quench detection threshold and/or variable validation delays that will depend on magnet current.

We support the baseline protection as presented, and endorse the proposal to provide variable quench detection threshold and/or variable validation delay-time that can be varied as a function of the magnet current.

We recommend to:

- Take steps to improve the QPHT-strip reliability, whereas particular emphasis should be given to the connection of the lead wires to the strips;
- Develop and validate a strategy for variable detection thresholds and/or validation delay-times, whilst assuring the requirement for high dependability of the system;
- Perform a detailed risk analysis including critical failure modes (e.g. trim-PCs).

2.3. Inner Triplet circuit and protection:

Circuit

The presented base line circuit design consists of two main PCs with two trim PCs, while the new proposal consisting of a single main-PC with an associated 3 trim-PCs.

We understand that operational experience with the current inner triplet circuit (2 main power supplies and one trim) has been – after a first learning period - positive.

We support the new proposal, which has several advantages over the previous baseline: improved beam dynamics by reducing tune variation, saving current leads and requiring only one high current PC in the main circuit.

We recommend, however, that the beam dynamics justification be well clarified again before going ahead with an engineering change request process, because more cautious design is inevitably required for the magnet protection system having larger stored energy and time constant in operation with the newly proposed single main PC circuit design.

Protection

The presented baseline protection design includes outer layer QPHT + CLIQ to provide appropriate redundancy, without external energy extraction. We understand that Inner/Inter-layer QPHT technology, as well as the reliability of the inner layer heaters, is still under investigation. A lot of work has been performed, including a very detailed risk analysis.

We comment that the essential conclusions from the risk analysis concerning the most critical failure modes and their mitigations should be extracted and highlighted.

We recommend to:

- Provide a summary table comparing the different basic options such as (i) outer quench heaters only, with and without quench back, (ii) outer quench heaters with CLIQ, and (iii) outer and inner quench heaters, with and without quench back;
- Investigate further the CLIQ technology, in particular, assess the long-time reliability and availability when applied for Nb_3Sn coils, and addressing the issues of cabling;
- Continue R&D on inner (and inter) layer QPHT, in particular to prevent degradation due to heater delamination;
- Proceed to study risk and comparative failure modes to justify the proposed single main circuit design in comparison with the alternative option of two main circuits consisting of Q1-Q2a

and Q2b-Q3.

2.4. D1 and D2 circuit and protection:

Circuit

The presented baseline circuit design consists of two independent PCs. The panel was not able to identify a strong request from a beam optics point of view for series operation of the two magnets. Furthermore, we were informed there would be no significant cost saving for powering the magnets in series (due to the additional components required for the powering and protection of the circuit with a single power supply, such as warm by-pass diodes, bus-bars and cables,…).

We therefore support the baseline choice of powering the two circuits independently.

Protection

The presented baseline protection design using QPHTs appears to provide sufficient protection. Increase of redundancy may be sufficiently implemented with additional QPHTs, and without CLIQ.

We support the baseline with the redundant QPHTs systems.

We recommend to further refine the analysis of the circuit protection during a quench, in particular for D2.

2.5. Inner Triplet higher order Correctors

The present proposal for triplet orbit-correctors MCBXF foresees protection using QPHTs, discarding the previous proposal to include external energy extraction. The design of most of the higher order (HO) correctors is to be changed to lower the operating current. For the quadrupole corrector MCQSX, it is proposed to keep the present baseline current of 180 A. Protection of HO correctors is passive with a fixed limit on the PC output voltage and by use of a crowbar.

We support the proposal for quadrupole correct MCQSX to keep the operating current at 180A and to lower the operational current for all other HO correctors to below 120A.

We recommend to re-consider energy extraction (EE) for the corrector MCBXF. Additional R&D is required to select the best option between protection using EE or QPHT.

2.6 Protection: Common Issues

We find that an integrated approach for powering and protection has not been yet systematically applied for all circuits including magnets, leads, links, and bus-bars.

We recognize that several novel and challenging technologies are required, including Nb_3Sn magnets, superconducting links, CLIQ, and high-current 2-quadrant PCs, in comparison with the current LHC magnet powering system.

We recommend to realize close and regular interaction (communication) between the involved experts and work-packages. This could be possibly done by setting-up of a dedicated working group or by using existing structures to discuss circuit integration and protection on a regular basis and to identify the optimum scheme for each magnet circuit system.

2.7. CLIQ: Common Issues

We find that the CLIQ concept has been well established, The CLIQ is proposed for the protection of the inner triplet quadrupoles in combination with QPHTs.

We support the implementation of CLIQ for the inner triplet quadrupoles, but the CLIQ technology with long Nb3Sn magnets needs to be well demonstrated.

We recommend that the CLIQ technology with long Nb_3Sn prototype magnets be demonstrated as soon as possible, together with efficient cabling and warm-cold connections. The effect of AC currents in the circuit and the eventual perturbations relevant for the protection of the SC link shall be fully analyzed.

2.8. Superconducting Link (SL)

We acknowledge the importance of the superconducting link and its requirement of unprecedented reliability to support the whole HL-LHC magnet in any operational mode and failure case.

We encourage thorough investigation in relation with the required level of reliability of the superconducting links.

Although this subject was not originally included in the review charge, a number of suggestions are provided in Appendix 3 in view of the importance of addressing relevant issues already at the conceptual design stage.

2.9. Electrical Quality Assurance and Voltage Withstand Levels

We find the baseline design to use a reference voltage and condition (temperature/pressure) per magnet based on worst case voltage scenario, for example GHe at 75 K and 1 bar in case of the IT quadrupoles and 11 T dipoles. Test voltages in air, gaseous or liquid helium are derived from the reference voltage by applying so called scaling factors. The strategy for the test in liquid helium is still under discussion. The strategy for turn-to-turn voltage tests still needs to be developed.

We support the standardized test-scheme proposed for the electrical quality monitoring of the magnets and associated components from manufacturing to commissioning/operation, as an interesting approach. On the other hand, acceptance tests and voltage withstand levels may have to be reconsidered based on feedback from the additional studies and from the manufacture and tests of magnet models/prototypes.

We recommend that test-voltage definitions should be reconsidered, based on previous experiences at LHC or other accelerators, as well as based on integrated experiences of the accelerator magnet fabrication and testing. We recommend more studies and tests to assess conditions with the worst-case voltages and the reliable test conditions to withstand to the worst case voltages.

2.10. Risk Analysis and Mitigation

We find that every complication of the magnet circuit and its powering will multiply efforts for operability and event analysis throughout many years of operation.

We suggest to keep architecture and implementation as simple & standardized as possible, putting emphasis on the provision of accurate and correct diagnostic data across complete systems.

We recommend to reinforce quantitative analysis of dependability of the entire protection system and its components, and to assess the use of redundancy technologies such as majority voting in an effort to maximize the dependability of the overall system.

2.11. String Tests

The string tests were proposed to be taking place in 2 phases, arriving relatively late in the project.

We strongly support the string test and its realization in 2 phases.

We recommend that a detailed test program be established, with clear objectives for each of the phases. All required effort should be provided to realize the first phase as early as possible. Fallback options in case of unavailability or delays from some of the components need to be worked out (D1, CP, power converters), as early experience will provide important input to many work packages.

We recommend the performance of an ultimate safety test such as the extreme case of an instantaneous and complete powering failure be included in the test program, to demonstrate the safety of the system before it is installed into the LHC tunnel.

2.12. Plan and Schedule, and Documentation

We believe the general schedule to be very tight, even if civil engineering (as one of the main pre-requisites for the upgrade) will be frozen soon.

We recommend a proper resource loaded schedule to be developed, in particular for the string test, considering concurrent activities such as LS2. Critical activities need to be identified and suitable resources to be allocated to cover critical activities.

3. Summary

This conceptual design review has been organized in timely manner for the efficient progress of the HL-LHC construction program. We, the review panel members, have been impressed with the already accomplished work and the presented thoughtful design studies, ensuring that the HL-LHC magnet circuits and their protection is efficient and reliable.

The required modifications of numerous magnet circuits in the High Luminosity insertions of the HL-LHC (higher peak field, higher current and larger stored magnetic energy, relocation of power converters and sensitive electronics far from radiation areas) make the system more complex and technically very challenging. The goal of the review was therefore to examine the baseline choices and evaluate the options for changes in terms of circuit topology, protection, integration, operation, voltage withstand levels and schedule.

Based on the presentations given to the review panel, a slightly different categorization has been chosen for the evaluation of the conceptual design of each magnet system taking into account their very different features. Therefore, we report the review results for each magnet system followed by common technologies, as follows:

Concerning the 11 T dipole circuit, the baseline is to have the 11 T dipole in series with LHC MBs and using correctors or a trim power converter for the required compensation. The operational mode with trims/correctors should be further investigated, including the related failure modes. For protection, the choice of a combination of QPHT and diode (without CLIQ) is supported by the review panel.

For the inner triplets, the new proposal featuring a single main power converter with 3 trim power converters is supported by the review panel, to be confirmed by more complete protection studies of the system as a whole to be reliable enough including the superconducting (SC) links. For magnet protection the baseline shall be using outer QPHT, plus CLIQ for redundancy. The option of inner/inter-layer QPHT is under investigation. A recommendation from the review panel is to assemble a summary table with relevant information allowing a comprehensive overview and comparison of the basic protection options.

For D1 and D2, the baseline is to maintain 2 independent circuits. Given the limited cost saving and no strong reasons from the optics point of view to adapt series powering, the review panel supports the baseline. For protection, redundant QPHTs provide sufficient protection, thus the use of CLIQ is not envisaged.

For the triplet correctors, the review panel supports the proposal to maintain the operating current at 180A for MCQSX, while other correctors will be re-deigned to allow for lower operating current (120A). It is recommended to reconsider Energy Extraction (EE) as an option for MCBXF in case quench heaters cannot be integrated in the magnet assembly.

As a general strategy for circuit protection, the review panel strongly recommends to maintain regular interaction among the involved WP leaders (possibly in the form of a working group) to systematically and coherently study and establish the integration and protection of the complete magnet circuit.

Concerning the use of CLIQ, the implementation for the inner triplets is supported, but this technology still remains to be demonstrated for Nb_3Sn magnets using their full-scale prototype programs.

The SC links were not included in the original scope for the review. As it represents a vital component of the overall powering circuit, it needs to be fully investigated with an emphasis on the electrical system integration and protection. The baseline relies on MgB_2 cables connected to flexible HTS cables forming the lower part of the current lead. While the R&D for the cable is well advanced, more system design work is still ongoing with respect to the integration and protection of the link as part of the magnet circuit system. Some suggestions are given separately in Appendix 3.

For High-pot/Voltage Qualification, it is proposed to use a reference temperature/pressure per magnet based on a worst case voltage scenario and to derive from this reference a ‘scaling factor’ for test voltages in air or gaseous helium. The definition of a final strategy nevertheless requires more experience with scaling factors and safety margins.

The risk analysis should be standardized to ease the comparison of different options and systematic dependability studies should be carried out in view of using new protection mechanisms such as CLIQ and to achieve the ambitious availability goals.

The string test in two phases is strongly supported by the review panel, and a detailed test program with clear objectives for each phase has to be defined. It may be advisable to include an ultimate safety test such as a full power failure mode during full system operation on the surface.

The schedule appears to be very tight, and the recommendation of the review panel is to develop a plan with necessary resources allowing for activities to be undertaken concurrently (e.g. during LS2 which partially coincides with the String test) and identify critical bottlenecks.

Acknowledgments:

We wish to thank all members of HL-LHC project for their impressive effort in preparing for the review, and advancing the project. We offer our sincere thanks for your warm hospitality during the review. Special thanks are addressed to Andrea Apollonio for his kind effort in summarizing our oral report to HL-LHC TCC (31 March, 2016), which is partially included in the summary of the review panel report given above.

References:

URL for the HL-LHC magnet circuit review:
https://indico.cern.ch/event/477759/

Executive summary of the review reported to
A. Apollonio "Minutes of the 5th meeting of the HL-LHC Technical Coordination Committee, held on 31 March, 2016.

Appendices:

Appendix 1
Review Panel Members and relevant persons:

- Guram Chlachidze (Fermilab)
- Arnaud Devred (ITER)
- Chen-Yu Gung (ITER, through remote contribution)
- Rudiger Schmidt (CERN)
- Davide Tommasini (CERN)
- Akira Yamamoto (CERN and KEK, Chair)
- Markus Zerlauth (CERN, Scientific Secretary)

Link person "Mr. HL-LHC Circuit":

- Felix Rodriguez Mateos (CERN)

Administrative Secretaries and contacts:

- Cecile Noel and Julia Cachet (CERN)

Appendix 2

The review meeting agenda is as follows:

3/21	Subjects	*Convener*/Speaker
8:30	Closed Session	*A. Yamamoto*
9:00	*Session 1: Setting the scene and cold powering*	*L. Rossi*
9:00	Welcome and scope of the review	Lucio Rossi
9:10	The HL-LHC magnets: status report	Ezio Todesco
9:40	HL-LHC circuits: global vie and open questions	Felix Rodriguez Mateos
	(Break ?)	
10:40	Integration of powering and protection systems	Paolo Fessia
11:20	SC links	Amalia Ballarino
12:00	Bus bars	Herve Prin
13:30	*Session 2: Protection of circuits & instrum.*	*Luca Bottura*
13:30	The principle of he CLIQ systems	Emmanuele Ravaioli
13:45	The 11 T dipole magnet and protection	Susanna Izquierdo-Bermudez
14:05	The 11 T dipole circuit(s)	Samer Yammine
14:25	The inner triplet magnets and protection	Giorgio Ambrosio
14:45	The inner triplet circuit	Emmanuele Ravaioli
15:05	D1	Tatsushi Nakamoto
	D2	Pasquale Fabbricatore
15:35	D1 & D2 circuit aspects	Felix Rodriguez-Mateos
16:20	Triplet orbit correctors	Fernando Toral
16:50	Triplet high-order correctors	Giovanni Volpini
17:20	Matching section correctors	Gijs De-Rijk
17:50	Closed Session	Akira Yamamoto
3/22		
8:30	*Session 3: Systems*	*Andrzej Siemko*
8:30	Operation requirements	Massimo Giovannozzi
9:10	Power converters: operational aspects	Jean-Paul Burnet
9:50	Quench detection	Jens Steckert
11:00	CLIQ & HDS units	Knud Dahlerup-Petersen
11:30	Warm cabling, cooling and ventilation	Laurent Jean Tavian
13:30	*Session 4: Elqa, MP3 and String*	*Ezio Todesco*
13;30	Electrical qualit assurance	Felix Rodriguez-Mateos
14:00	Diagnostics and analysis: the point of view of MP3	Arjan Verweij
14:30	Inner triplet string	Luca Bottura
15:30	Documentation plan	Reiner Denz
16:10	Roadmap for decisions	Daniel Wollmann
16:40	Closed session (followed by working dinner)	*Akira Yamamoto*
3/23		
8:30	Panel Closed Session	*Akira Yamamoto*
12:30	Review Panel Lunch	*L. Rossi*
14:00	Panel Closed Session	*Akira Yamamoto*
16:00	Close-out by Panel	Akira Yamamoto
17:00	Adjourn	

Appendix 3

Additional suggestions/remarks

Several important aspects of the powering systems were deemed to be not part of the charge of this review, which was aimed at reviewing the circuits at the conceptual level and with the purpose of establishing an agreed baseline for further studies, e.g. for the dimensioning of the superconducting link. As all elements will ultimately be part of one common magnet powering systems, several relevant aspects have been part of the discussion and the review panel considers it worthwhile to record their result in order to be useful for the further development of the powering system.

Power converters

We were reported that the use of SC links and the consequent reduction of the series resistance. It is considered to use high-current 2-quadrant PCs instead of the conventional 1-quadrant converters presently used for powering circuits with a single polarity. With such power converters, the stored magnetic energy can be recovered into temporary storages such as batteries, or sent back to the network, thus reducing the power consumption of the laboratory. The EPC group is proposing to develop/purchase such devices with characteristics suitable for powering the quadrupoles. While not a fundamental requirement for the HL-LHC project, this would appear to be an interesting initiative that could lead in the long term to considerable energy savings and hence contribute to the ecological efficiency of CERN and other laboratories, hence the review panel supports such developments. However, it has to be shown that such power converters can be controlled with the same degree of precision – or better, as higher precision is a must for the triplet PCs. It has to be clarified whether such additional R&D should be included in the HL-LHC budget.

The PCs were not on the list of items to be reviewed and we were not shown sufficient detail about the internal circuits to be able to judge what impact these have on the protection of the system.

Quench Heater Power supplies

Quench heaters are part of the baseline protection system for the 11T and IT magnets. Large delay times in triggering the quench heater supply discharge may compromise the magnet protection. The review committee recommends to improve (reduce) the current trigger delay time of 4 ms.

Superconducting Links

Powering of the new insertion magnets requires power converters to be placed in the new UA galleries, protected from radiation, with superconducting links of up to a length of 100 m. The baseline design for such links is to use MgB_2 cables inside a flexible cryogenic line connected to flexible HTS cables at the power converter side, and to NbTi cables on the magnet side. The proposed cable assembly includes several circuits. This option enables an operation of the link in gaseous/supercritical/liquid helium with a temperature sufficiently lower than about 20 K. The review panel considers powering with a superconducting link to be a very interesting and novel solution, requiring however additional R&D efforts and added complexity for its integration as a flexible HTS link. The sc link is an essential part of the system that has to be fully and reliably integrated with the magnet circuit systems.

We appreciate the effort that has been invested in successfully developing a 20 kA MgB_2 cable, and the conclusive test of the demonstrator. The cable architecture may however need to be modified to take into account changes proposed to the baseline in the high current circuits (QXF, D1, D2). By removing the energy extraction systems, the magnets can only be discharged either by firing quench heaters (less than a second discharge time) or via the power converter (about 1000 s discharge time). Therefore, emphasis should be put in the exploration of an option capable of sustaining the controlled magnet ramp down, including a clear development plan to be established for the required joints (HTS/ MgB2 and MgB2/NbTi). We fully understand that such studies are ongoing, but wish to point out the importance of optimizing the parameters and technical choices addressing the new baseline conditions, including a comparison with other approaches to conveying the current, e.g. based on a LTS link or on a conventional (resistive) cable to compare the options with respect to their operational performance, engineering effort, development and construction cost as well as maintenance and cost during operation.

The value of fostering the novel technology, which could be useful for application to projects other than powering the LHC insertions, is important, and the magnet group should make available the necessary resources for carrying out the necessary design and prototyping work in a timely fashion. As final validation, the link technology should be demonstrated during the Phase 1 string test, including the demonstration of the quench detection system and systematic studies of cross-talk between circuits for different failure scenarios.

Bus-bars and Cabling

We were shown a preliminary design and layout for the superconducting bus work inside the cold masses. This is work in progress that appears to be on the right track. It will need to follow the evolution of the powering circuits. The newly proposed powering scheme without energy extraction raises similar questions regarding cross-sections of conductors and joints to those mentioned above, as well as the dimensioning (and technology) of the lambda plate passage.

In addition to the bus bars carrying the excitation currents for the magnets, there are numerous wires and cables for voltage taps, temperature sensors, quench heaters and the powering of CLIQ that have to be routed from inside the cold masses to the room temperature environment. The CLIQ cables need to be fairly thick, be a.c. compatible, and both routing and heat load need to be taken into account.

As a side comment, we were informed that a recurring problem in the current LHC is the disconnection/re-connection of DC cables to HTS leads (during ELQA, fault finding). Where new current lead boxes are installed the design should address this concern. We also recommend the study of possible improvements to the present installation, e.g. proper fixation in the waiting position and/or circuit separators for the HL-LHC.

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