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FINAL

Review Panel Report for The 2nd International Review of the HL-LHC Magnet Circuits

9-10 September, 2019

Review Panel Members:

Hans-Jörg Eckoldt (DESY), Jim Strait (FNAL), Neil Mitchell (ITER), Paolo Fessia (CERN), Stephen Gourlay (LBNL), and Akira Yamamoto (KEK-CERN, Chair)

Link Person: Felix Rodriguez Mateos,
and
Scientific Secretary: Samer Yammine

Scope of the Review:

The Review Panel has been asked to review/assess the following mandates:

1. Final design/layout of the HL-LHC magnet circuits,
2. Protection of the magnets and circuits,
3. Integration of equipment, respecting installation and maintainability requirements,
4. Instrumentation for protection and for the ancillary equipment,
5. Electrical quality assurance strategy, making sure of insulation coordination, and
6. Magnet circuit string (IT+D1) system tests in operational conditions at SM18.

The full review scope is given in Appendix 1 and also available at:
https://indico.cern.ch/event/835702/

Executive Summary

Overview:

The 2nd International Review of HL-LHC Magnet Circuit was held on 9-10 September 2019. The Review Panel (Committee) thanks the CERN HL-LHC management and staff for the hospitality during this meeting and all the presenters for their excellent talks and the highly interactive discussions.

The Panel has understood the HL-LHC magnet circuit design well advanced since the previous reviews held in 2016 and 2017. Advices from previous magnet circuit reviews in 2016 and 2017 have been well implemented in the updated design, and they are appropriately reported in the review.

The Panel supports the magnet circuit design concept presented. The Inner Triplet (IT) quadrupole system (MQXF) is powered in series by using a main power converter (PC) with nested trim PCs and the current supplied/transmitted by using MgB_2 superconducting links. The IT quench protection is provided by using the Coupling Loss Induced Quench (CLIQ) system and Quench Protection Heaters (QHs). Separation and Recombination dipoles (D1 and D2) and further quadrupoles are individually powered and protected by QHs. Corrector magnet circuits are individually powered and the quench protection is also individually optimized, partly using energy extraction, based on inductance and stored energy. The 11 T dipole (MBH) is operated in series with arc main dipoles (MBs) and nested trim PCs are required for harmonizing the excitation characteristic with other MBs. The control and precision of the PCs, Quench Detection/Protection system (QPS), and associated instrumentation have been significantly advanced to meet HL-LHC requirements.

The Panel strongly supports the SM18 string test plan, as a critical milestone in the HL-LHC project. It will provide a unique opportunity to verify critically important magnet circuit aspects not testable with single magnet tests. It also provides an opportunity to understand installation and commissioning issues prior to LS3, and contribute to examine overall safety and training to emergency actions during the system operation. It will practically reduce the main project risk and save the time to complete the HL-LHC construction.

Two different QH configurations were presented: MQXF-QHs "impregnated" with the coil, and MBH-QHs "externally" placed outside the impregnated coil. This difference has been justified mainly on the basis of the different voltage requirements (~ x2 for the MBH) and of the different model/prototype work results. The QH design change (for MQXF) in this stage would also cause more risk than benefit, in the project time constraint. This topic was also discussed at the MQXF review in July 2019, and two recommendations resulted: "Assess the QH design including the assembly process, to justify the current baseline design, and prepare for any unexpected incidents during production" and "Assess the long-term stability of the quench heaters including epoxy impregnation issues (elimination of bubbles and dry spots)". These recommendations have been fully understood by the Panel. If any change is necessary, it needs to be clearly justified in the HL-LHC Project Team.

There are significant discrepancies between simulation results for some self-protected corrector magnets. Most are understood qualitatively but benchmarking with actual magnet tests including failure scenarios are ultimately required to define operating parameter envelopes.

A new configuration of MgB_2 superconducting link with the Distribution Feedbox HTS-end (DFH) is proposed to provide the interface from the MgB_2 superconducting link to the HTS power leads. This design will be attractive if it can be translated in an engineered solution with all ancillaries. The conceptual design review is scheduled in November 2019.

A set of requirements for voltage withstand levels has been established, including those **(i)** under initial room temperature conditions, **(ii)** at nominal operating conditions (NOC), and **(iii)** at room temperature after the coils exposed to helium. However, ultimate voltage criteria representing conditions close to a quench are not yet established as these criteria represent the peak voltages during the quench at conditions difficult to obtain in the test stations. Therefore, an additional test **(iv)** at intermediate temperature and pressure in helium gas on superconducting magnets is proposed. It may be integrated in the production process without major time impact, and no counterarguments are found.

Safety and risk analyses have been carefully assessed. The importance and effectiveness of the beam abort action before the quench protection system functioning has been well understood.

The magnet circuit design and development have been sufficiently matured to get into the construction phase.

Recommendations:

R1: Address the recommendations for the QH configuration and quench protection scheme, given by the MQXF review in July 2019. Provide solid justification in the HL-LHC Project Team, if any change is necessary.

R2: Improve understanding of the significantly different results obtained from different quench simulations for some self-protected corrector magnets and make the reasons for the differences clear. Experimental results shall be carefully reflected to figure out the appropriate protection.

R3: Verify the newly proposed Distribution and Feedbox HTS-end (DFH) concept for the superconducting link. Ensure the impacts and dependencies on the whole system.

R4: Strengthen the electrical quality assurance guideline and the voltage withstand test plan. Add the fourth test plan at an intermediate temperature and an appropriate pressure in helium gas environment, reinforcing the three test conditions already established.

R5: Justify the voltage withstand level to be relatively consistent to each magnet and circuit design. It should be clearly compared, documented, and shared as a common document in the Project Team.

R6: Establish the (IT+D1) string test plan at SM18 and execute it within the period between now and LS3. Ensure the performance for the inner triplet nested (4 coupled) circuits and the overall system including the MgB_2 superconducting link. Reinforce the string test team to accomplish the goal within the limited time.

Complete Report:

I. Introduction

The 2nd International Review of HL-LHC Magnet Circuit was held on 9-10 September 2019. The Review Panel received 20 contributions in open sessions and 7 contributions in a closed session. The Panel has understood that the magnet circuit design and development have been much advanced since the 1st international review held in 2016. The review scope and information are available at:

https://indico.cern.ch/event/835702/

II. Finding/Comments and Recommendations to Mandates:

1. **Review the final design/layout of the HL-LHC magnet circuits including the aspects related to powering and quench protection strategies, making sure that the right choices have been made both in terms of circuit optimization and protection reliability;**

Findings/Comments:

<u>IT Quads (MQXF) Circuits:</u>

- The overall circuit layout/design has significantly converged since the 1st international review, to power all 4 magnets in series (18kA), using 2 kA trims on Q1 and Q3 to tune the optics.
- The magnet protection relies on CLIQ and QHs, to maintain T-max (hot-spot) < 350 K.
- The 35 A trim at Q1 has been added for k-modulation (β*) measurements. The effect of the 35 A modulating trim on the overall regulation of the IT 4-coupled/nested circuit should be carefully assessed and tested to ensure that there is no disturbance due to crosstalk. It should be demonstrated in the string test at SM18.

<u>IT Higher Order Corrector Circuits:</u>

- The skew-quadrupole magnet (200A) is protected via energy extraction with a 1.5 Ohm resistor grounded at the mid-point. The rest of the magnets – sextupole, octupole, decapole, and dodecapole – (100A) are self-protected.
- These correctors will be powered by PCs located in existing LHC underground areas (UL, USC).

<u>Separation and Re-combination Dipole (D1& D2) Circuits:</u>

- The baseline design is to power the two magnets (14 kA) using independent PCs. The protection is ensured by using QHs to maintain T-max (hot-spot) < 300 K.

<u>Nested Dipole Corrector (MCBXF) Circuits:</u>

- The MCBXF is composed of two nested and individually powered horizontal and vertical dipoles (1.6 kA).
- It will be used in two configurations: 2.5m-long (-A), 4.5 T-m protected via energy extraction, and 1.5m-long (-B), 2.5 T-m, self-protected (this point remains to be confirmed.)

<u>11T Dipole (MBH) Circuits:</u>

- Each full assembly will be composed of two 5.5m-long magnets with a collimator in between to replace a regular 15m-long LHC dipole. The magnet will be connected in series with the MB circuit.

- A 250A trim PC will be used to compensate any differences in the transfer function with respect to the main LHC dipoles. The trim circuit will require a custom configuration for protection and interlocks. Magnet protection is provided by quench heaters in conjunction with energy extraction.
- 11 T dipoles will be the first Nb_3Sn superconducting magnets in HL-LHC and in LHC to be installed during LS2.
- Flux jumps are a general concern for all the Nb_3Sn magnets as they are expected to impact operational stability and quench detection. More needs to be learned via upcoming tests (variable quench detection voltage thresholds).

<u>MgB_2 Superconducting link:</u>
- The MgB_2 superconducting link design has been much matured with further optimization of the configuration and robustness in stability and sustainability in case of quench.
- The development has been significantly advanced and the general performance has been demonstrated with the 60 m long prototype test at SM18.

<u>PC Precision Control:</u>
- The precision control for the HL-LHC power convertors (PCs) has been much advanced to reach a level of 1 ppm or less during the ramping and in steady operation, so called the Class “0” for IT, D1 and D2 : two to three times better than that of the LHC PCs.
- This progress is critically important to meet the HL-LHC beam dynamics requirements.

<u>Safety and Risk Analyses:</u>
- Safety and risk analyses have been carefully assessed.
- The importance and effectiveness of the beam abort action before the quench protection system functioning has been well understood.

<u>Lessons learnt from LHC</u>
- It has been recalled that the largest part of LHC electrical issues have been localized in the bus bar bundles or instrumentation wires.
- As consequence this underlines the importance of having sturdy and robust insulation systems for those sub-systems. This is especially true for the IT area where all interventions will be strongly limited because of the activation. The positioning of the bus bar can affect the voltage difference seen by adjacent conductors during fast power abort. Such difference could therefore be reduced in the design phase reducing the voltage stress in operation.

Recommendations:
- Ensure the control for the inner triplet nested circuits (4 coupled circuits to be controlled, including 35A K-modulation on Q1a). This circuit for β^* measurement needs to be controlled with the required performance.
- Verify test plan to be executed in the IT circuit string test at SM18 as a unique opportunity on surface.
- Verify MgB_2 superconducting link and NbTi bus-bar design, their relative position and relative elements movement during cool down and energization in the string test.

2. **Review the adequacy of the protection of the circuits for the different configurations that are adopted in order to assure safe commissioning and operation with beam. This aspect includes protection in case of quenches, failures of various components or of systems, effects of protection equipment to beam, protection of power converters, etc.;**

Findings/Comments

<u>CLIQ</u>

- CLIQ will be used for the IT Quads combined with QHs.
- There has been considerable progress since that 1st international review. There is still remaining concern on reliability, as this is the first use of CLIQ in an operating accelerator.
- R&D at CERN and FNAL continues toward making the system machine-ready and a conceptual design is being finalized. So far, a redundant trigger and discharge path have been added.
- Studies and tests have indicated that the system meets reliability requirements for HL-LHC.

<u>Quench Protection Heater (QH)</u>

- Many of the HL-LHC magnets rely heavily on the effectiveness and reliability of QHs. The importance of the development of a robust design cannot be overemphasized.
- It has been well understood and agreed that placing the QH on outer surface of the coil is the solution in order to minimize risks for delamination caused by excessive helium gas pressure from possible voids due to superfluid helium penetration between the coil and QH. On the other hand, including the QH in the impregnated coil reduces the quench delay and therefore the peak temperature.
- Two different QH configuration were presented: MQXF-QHs are impregnated with the coil, and MBH-QHs are attached to outside of the impregnated coil (so called "external-QH"). This difference was justified mainly on the basis of the different voltage requirements (about x2 for the MBH), as summarized by F.R. Mateos' second report (page 20), and the different R&D results from the model program. It was also considered the QH design change (for the MQXF) in this stage would cause more risk than benefit in the project time constraint. This topic was also discussed at the July 2019 review of the MQXF, and two recommendations resulted: "Assess the QPHT design including the assembly process, to justify the current baseline design, and prepare for any unexpected incidents during production" and "Assess the long-term stability of the quench heaters including epoxy impregnation issues (elimination of bubbles, dry spots and cracks)." The panel fully supports the recommendation from the previous review. If any change is necessary, it needs to be clearly justified in the Project Team. Two alternate options for the MQXF are being investigated: to swap one layer of fiberglass cloth from above to below the QH to increase safety margin within the impregnated QH category and to put the QH outside of the potted coil.

<u>Quench protection hardware and instrumentation</u>

- The quench protection hardware and associated instrumentation has been developed with much enhanced capability for quench detection, the integrated data-acquisition system offering significantly higher sampling rates and resolution, based on the analog/digital converters and Field Programmable Gate Array (FPGA) technology. All the system design has been redundantly made.
- Recent tests with prototype magnets and superconducting links have confirmed the validity of the design and performance.

<u>Simulations</u>

- The protection studies are distributed among CERN and external institutions as a means of cross checking. In cases where results are marginal, the worst realistic failure scenarios are considered.
- There are significant discrepancies between simulation results, for some self-protected corrector magnet simulations, possibly because of different input parameters. Most are understood qualitatively but benchmarking with actual magnet tests including failure scenarios are

ultimately required to define operating parameter envelopes.
- It should be clarified which simulation results are being trusted for each magnet and why. Information should be clearly noted and errors bars should be added on shown data.
- The computations assumed as reference for the design choices should be clearly indicated and the reason why have been selected should be clearly motivated.
- The effect on the beam induced by the quench protection actions (QHs and CLIQ) should be carefully studied and mitigated, reflecting the experience integrated in the LHC operation.
- Defining maximum hot spot temperatures is a standard way of determining magnet protection systems, but the committee agrees with the proposal to include thermal strain in addition to hot spot temperature for the Nb_3Sn magnets.
- The effect on the results from the variability of the activation of the various discharge/heater/CLIQ systems should be shown on the voltages and the hot spots. Their amplitude shall be clearly and separately shown.

Voltage Withstand Levels
- The voltage limit on refurbished coils seems not be completely solved. The set of test voltages executed by the team is quite complex. It should be well defined in a unified engineering document with their rationales clearly stating when concessions have been done to avoid too high rejection rate and what such concessions means in the loss of capability to detect defects. It should include the possible test and requirement at an appropriate temperature in helium gas environment during the course of the magnet and circuit test.
- Intermediate-temperature test on the magnets proposed by the team and it may be integrated in the production process without major impact. No counterarguments have been found.
- It should be important to push the standardization a step further ensuring it through the collaborations around the world, and in the different manufacturing sites. The “local” electrical test plans and protocols should be provided to CERN to be endorsed before their application.

Recommendations:
- Complete a consistent guideline of the QH design criteria for two different concepts of “external QH” and “impregnated QH” to be applied to the MBH and MQXF.
- Address the recommendations from the July 2019 MQXF review regarding the QH. Provide solid justification coherently for alternate options being investigated in the HL-LHC Project Team, if any change is necessary.
- Improve understanding of the significantly different results obtained from different quench simulations and make the reasons for the differences clear. Experimental result shall be well reflected to the protection design. In case the design process relies more on a simulation than another, the technical reason for the choice shall be clearly stated and traced.
- Reinforce the electrical quality assurance guideline and the voltage withstand test plan, including the additional (iv) intermediate temperature voltage test in helium environments, in addition to the three categories already established. Ensure it to be clearly documented for each magnet including justification for the differences, and to be well shared in the Project Team.

3. **Review the integration of equipment respecting installation & maintainability requirements:**

Findings / Comments:
- The powering and protection system are firmly integrated in terms of space, which means also strong interlink in terms of accessibility, installation-ability, maintainability and safety.
- Safety for personnel will be guaranteed only if all the equipment installed are dealt as a unique

system avoiding creating weak elements at the interface. Later management of such issues tends to be costly, bulky and time consuming.

- All equipment installed in the areas which are accessible to personnel during operation (i.e. the URs) should be designed in conformity to the required standards as set by the HL-LHC Project. This is of particular relevance for electrical power systems (converters, CLIQ, energy extraction units, etc).

Recommendations:

- Ensure the impacts and dependencies on the whole superconducting current DFH system, to be carefully accounted for, power converters, magnet protection, cryogenics, and others. The personnel safety as well as maintainability and installation ability shall be carefully integrated in the design criteria. General integration constraints as well as project schedule and installation available time shall be factorized in the development.

4. Review the proposed instrumentation for protection, the ancillary equipment (feeders, feedthroughs, etc.):

Findings/Comments:

- The redundant instrumentation has been carefully considered.
- The review should address the MgB_2 feeder layout, design parameters (voltage, discharge) and testing. Ad-hoc technical review should be carried out on the detailed technical design of the joints and connections inside the units and between them. A similar action shall be also taken to review the matching QC plan. This is important for the MgB_2 to Nb-Ti connections.
- The project has decided not to integrate spare cables inside the SC link. As consequence reliability of this element and the possibility to reduce as much as possible the impact of its change shall be taken care of in the design and integration.

Recommendations:

- Establish the design base on joints and connections between subsystems before finalizing the design for fabrication. A detailed design review shall be organized.

5. Assess on the Electrical Quality Assurance strategy of cold/warm equipment and circuits, making sure that (electrical) insulation coordination is properly established.

Findings/Comments:

- Documentations for the Quality Assurance (QA) strategy has been well progressed.
- A well-developed set of required voltage withstand levels was presented including those (i) under initial room temperature conditions, (ii) at NOC, and (iii) at room temperature after the coils have been exposed to helium.
- However, ultimate voltage criteria would not be yet established as these sometimes represent a balance of the peak voltages at an extreme condition. Therefore, an additional test **(iv)** at intermediate temperature and environment on superconducting magnets is proposed. It may be integrated in the production process without major time impact, and no counterarguments are found.
- Such criteria should be also clearly defined and documented to the voltage test between the QPHTs and Ground, as similar as Coil to GND and Coil to QPHTs

Recommendations:

- Reinforce the voltage withstand test plan, including the intermediate temperature voltage test in helium environments, in addition to the three categories already established for the initial test in air at RT (300K) before cooldown, the test in NOC, and the test after warm-up (with residual helium) at RT, as recommended in section Mandate 2).
- Complete the electrical quality assurance plan, ensure it is clearly documented, efficiently shared in the HL-LHC Project Team, including all collaborations and suppliers.
- Collect the electrical test plans adopted at the different premises. Check them for coherence and compliance with the central project electrical quality assurance plan.

6. System tests in operational conditions in the IT String;

Findings/Comments:

- The Panel strongly supports the SM18 string test plan, as a critical milestone of the project to be completed before LS3. It will provide a unique opportunity to verify many electrical circuit aspects not testable with single magnet tests.
- It provides an opportunity to understand installation and commissioning issues prior to LS3, which will practically save much time to reach the HL-LHC construction project completion.
- It will contribute to reduction of the main project risk, by identifying issues not foreseen by individual magnet tests or analyses, and by examining overall system-safety, during the system operation.

Recommendations:

- Establish the IR (IT+D1) string test plan at SM18, and execute it within the planned period between now and LS3, focusing on 4-coupled/nested circuits to be controlled (k-modulation) for the inner triplet, superconducting link, quench protection in combination of CLIQ and QH, and overall safety aspects including extreme emergency actions.
- Reinforce the string test team to accomplish the goal within the limited time,
- Prepare the system quality assurance to be systematically confirmed at the SM18 string tests.

Acknowledgment

We wish to thank all members of HL-LHC magnet circuit collaboration/forum for their significant effort to advance the project and to preparing for the review and valuable discussions made during the review. Special thanks for Felix Rodriguez Mateos as the Link Person, Samer Yammine as the Scientific Secretary, and Elodie Kurzen as the Administrative Secretary.

A group photo from the 2nd Int'l review on the HL-LHC magnet circuit review.

Appendices

Appendix 1:

The 2nd Int'l Review 2019: Mandate (originally given by HL-LHC management)

The Panel is invited to:

1. Review the final layout (design) of the HL-LHC magnet circuits including the aspects related to powering and quench protection strategies, making sure that the right choices have been made both in terms of circuit optimization and protection reliability;
2. Review the adequacy of the protection of the circuits for the different configurations that are adopted in order to assure safe commissioning and operation with beam. This aspect includes protection in case of quenches, failures of various components or of systems, effects of protection equipment to beam, protection of power converters, etc.;
3. Review the integration of equipment respecting installation & maintainability requirements;
4. Review the proposed instrumentation for protection and the ancillary equipment (feeders, feedthroughs, etc.) and its test in operational conditions in the IT String
5. Assess on the Electrical Quality Assurance strategy of cold/warm equipment and circuits, making sure that insulation coordination is properly established.

While this is mainly a technically oriented review, (managerial aspects are reviewed by special Cost & Schedule Reviews) the Panel may comment on the level of integration and collaboration between various Work packages and teams participating to the circuits design and realization.

Appendix 2:

Previous Reviews in 2016 and 2017 and Charges:

- **The 1st International Review for the Conceptual Design of the HL-LHC Magnet Circuits,**
  - Date: 11-13 March 2016
  - Review Panel Members: Guram Chlachidze (Fermilab), Arnaud Devred (ITER), Chen-Yu Gung (ITER), Rudiger Schmidt (CERN), Davide Tommasini (CERN), Akira Yamamoto (KEK-CERN, Chair), and
  - Scientific Secretary: Markus Zerlauth (CERN)
  - **Charges:** Circuit Topology, Magnet and Circuit Protection, Circuit Integration, Operation, Voltage Withstand Levels, and Plan and Schedule

- **HL-LHC Magnet Circuits Internal Review,**
  - Date: 17 March 2017
  - Review Panel Members: Luca Bottura, Lucio Rossi (Chair), Rudiger Schmidt, Andrzej Siemko, Thomas Taylor, Davide Tommasini and Akira Yamamoto
  - Scientific Secretary: Felix Rodriguez Mateos
  - **Charges:** to examine the choices presented at the review meeting 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, and Inner Triplet Main Circuit.

Appendix 3:

List of contributions presented, See URL: https://indico.cern.ch/event/835702/

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9 September:

--- Closed session ---	
HiLumi Status and Charge to Review	*Lucio Rossi*
Quick Overview on the HL-LHC (IR region) Magnets Characteristics	*Ezio Todesco*
Introduction to HL-LHC Circuits and Report from Prev. Review	*Felix R. Mateos*
Warm Powering and Adequacy with Respect to Requirements	*Michele Martino*
--- *Break* ---	
Cold Powering	*Amalia Ballarino*
Superconducting Bus Bars Inside Cryostats	*Ezio Todesco*
Quench Protection Strategies	*Arjan Verweij*
---- *Lunch* ---	
Quench Detection, related Hardware and Required Instrumentation	*Reiner Denz*
Quench Protection Hardware	*David Carrillo*
Design for the Protection and Diagnostic Feeders of the HL-LHC Triplets	*Lloyd Ralph Williams*
Contribution of Power Converters to the Protection of the Circuits	*Samer Yammine*
Effects of Protection Equipment on the Beam and Reliability Studies for the Circuit Protection Systems	*Daniel Wollmann*
--- *Break* ---	
Integration Studies	*Michele Modena*
Voltage Withstand Levels	*Felix Rodriguez Mateos*
--- Closed session ---	

10 September:

11T MBH: Electrical Integrity and Quench Protection Test Results	Frederic Savary
(IR) MQXF: Electrical Electrical Integrity and Quench Protection Test Results	Giorgio Ambrosio
NbTi magnets: Electrical Integrity and Quench Protection Test Results	Arnaud Pascal Foussat
--- Coffee break ---	
Document Plan, Management of Change	Samer Yammine
The HL-LHC Inner Triplet String	Marta Bajko
Safety Aspects	Thomas Otto
--- Closed session---	
Risk analysis of the string system	Marta Bajko
Table with voltages and temperatures on QXF magnets	Emmanuele Ravaioli
Voltage withstand levels and quench heater position for QXF and 11T MBH	Frederic Savary
Splices in HL-LHC cryostats	Herve Prin
Reliability of the complete inner triplet circuit protection	Andrea Apollonio
Feedback from LHC and MDs done with respect to effects to beam by misfiring of protection	Daniel Wollmann
How to guarantee security of firmware in quench detection and potential protection implications	Reiner Denz
--- Close out ---	Akira Yamamoto, and Review Panel

Appendix 4:

Minutes of the Reports and Discussions
at
"The 2nd International Review of HL-LHC Magnet Circuits"

reported by
Scientific Secretary, Samer Yammine

The minutes is also available on the circuit review indico page:
https://indico.cern.ch/event/835702/

The presentations during the review had taken place according to the program shown in appendix 3. Every presentation was followed by five minutes discussions. A dedicated session focused on topics that the panel requested took place on Tuesday 2019-09-10/13:30-16:00. The following notes reflect the presentation and the discussions.

HiLumi Status and Charge to Review – L. Rossi

Firstly, L. Rossi presented the planning of the HL-LHC project and recalled that the targeted integrated luminosity is 3000 fb^{-1} during the HL-LHC lifetime and 4000 fb^{-1} in ultimate conditions. He recalled also that the heart of the HL-LHC project is the upgrade of the triplet magnets in points 1 and 5 of LHC. He showed the role of the magnet circuit forum in the upgrade of the HL-LHC magnet circuits and the interactions with the different work packages. He showed the overview of the construction of the magnets as well as the cold powering systems for HL-LHC and emphasized that the project is half-way between the beginning of the design study and the installation and commissioning of the HL-LHC equipment. He showed that an overview of the string test that is planned at SM18 test facilities and announced that the actual testing is planned in 2023. After showing the civil engineering status of the project, he announced the charge overview and introduced the names of the panel members.

J. Strait asked if all the magnets planned to be installed for the string test are series magnets. L. Rossi replied that the magnets will be either prototypes, pre-series or series (from Q1 to D1). After a question by N. Mitchell, L. Rossi announced that, even if the systems are in advanced design level, any comment or input on the design is welcome by the project.

Quick Overview on the HL-LHC Magnets Characteristics – E. Todesco

E. Todesco showed a general introduction to the magnet designs and relevant aspects of the requirements, in particular the ones related to powering, protection and optics. He listed the magnets from Q1 to D2 including the different orbit and high order correctors. He showed the main requirements in terms of current, quench protection scheme and operation requirements from optics viewpoint.

Concerning a question on the protection scheme of the MCBXFB (short inner triplet orbit corrector), E. Todeso said that tests are undergoing and the outer dipole magnet may need an energy extraction system.
S. Gourlay interrogated about the 200 K limit imposed for the NbTi corrector magnets and 300 K on the main magnets (D1 and D2), E. Todesco confirmed this limit except for the MCBXF magnets (300 K limit). He stated that a higher limit for the correctors could be reached though.

Concerning the voltage to ground and the hot spot temperature calculations, E. Todesco stated that the quench simulations take into account failure scenarios that will be shown in A. Verweij's talk.

S. Gourlay asked if quench back is integrated in the simulations, A. Verweij replied that this depends on the circuits. For instance, to simulate the inner triplet circuit, quench back is necessary due to the presence of CLIQ. The big part of the simulations of the other circuits with active quench protection do not consider quench back.

Introduction to the HL-LHC Circuits and Report from Previous Review – F. Rodriguez Mateos

A global view on the baseline of the HL-LHC circuits and a synopsis of the choices that were made to reach it were presented by F. Rodriguez Mateos. The outcome of the CERN Internal Review of the HL-LHC Magnet Circuits in March 2017 and the implementation of the follow-up of the recommendations were also presented. F. Rodriguez Mateos gave an overview of the magnet circuit forum activities and showed the structure of the review.

A. Yamamoto asked about the three-cable configuration (inner triplet and D1 connection) and the reason behind calling this configuration as degraded. F. Rodriguez Mateos replied that this configuration could be used if a cable of the super conducting link is damaged, and permits powering the inner triplet and D1 with three 18 kA cables. However, F. Rodriguez Mateos emphasized that big modifications should be undergone to allow this connection.

Following a question by J. Strait, F. Rodriguez Mateos confirmed that the Q1a trim power converter act as a path for the CLIQ discharge as the warm diodes ensure for Q3a. In addition, J. Strait asked about the connection of the 11T MBH magnet on circuit RB.A67 and the asymmetry in the circuit, S. Yammine confirmed that this is linked to the A type of the MBH replacing a type B MB. S. Yammine confirmed that one design is intended for the MBH and, in sector 78, the connection is symmetrical.

Warm Powering and Adequacy with Respect to Requirements – M. Martino

In order to achieve the requirements of the HL-LHC optics and in adequacy with the LHC machine, the power converters have strict requirements on performance. M. Martino described the main challenges for the power converters for HL-LHC especially regarding precision and high availability. He then presented the power converters used for HL-LHC, namely the 18 kA power converter that contains a battery system to recuperate the magnetic energy from the circuit. He showed the modular and redundant design of the HL-LHC power converters. Afterwards, he described the control algorithm implemented for the converters control, and the decoupling control for the HL-LHC inner triplet circuit.

H.J. Eckoldt asked about the position grounding of the main power converter of the inner triplet circuit. S. Yammine replied that, since the power converter and crowbar voltages are 10 V at most, placing the grounding system in the midpoint of the power converter does not have major impact on voltages to ground.

L. Bottura asked about the rating of the warm diodes. S. Yammine replied that these elements would be rated to absorb transitory currents of up to 4-5 kA for short durations of hundreds of milliseconds (5 MIITs).

Cold Powering – A. Ballarino

The cold powering systems for HL-LHC are presented by A. Ballarino. She presented the systems and the superconducting cables from the current leads to the lambda plate and the different interfaces with the systems. Afterwards, she presented the current rating of the cables and current leads as well as the protection strategy. The voltage withstand requirements are also presented. A. Ballarino, then, presented the electric systems design (MgB_2 link, electrical feed boxes and current leads) and she stated that a new concept of the electrical feed box (DFHX) in the UR galleries is proposed and will be evaluated. The Demo 1 test was also presented where a cryostat with two MgB_2 wires were tested in machine conditions and further.

S. Gourlay asked whether the electrical design criteria are determined at nominal conditions or ultimate. A. Ballarino stated that the current rating of the elements is higher than the ultimate current and the voltage withstand is determined at nominal. F. Rodriguez Mateos replied that the strategy of the voltages withstand levels will be presented in his talk later in the same day. A. Yamamoto asked if a higher field is expected in the string test with respect to demo 1 test. A. Ballarino replied that, given the cable geometry and the position of the cable of opposite polarities, the resultant fields in the link in machine operation would be similar even smaller than in the test. She added that the demo 2 tests would include test of two sets of two cables.

H.J. Eckoldt interrogated on the impact of the proximity effect on the cables. A. Ballarino stated that these effects were not observed since the cables demonstrate shielding capabilities. After a question by J. Strait on the test results on demo 1, A. Ballarino informed that discharges were performed, in addition to quench by overheating, AC losses tests, splice resistance tests and different anomalies. She stated that a test report will be available by the end of the year, but a presentation is available with the test results.

N. Mitchell asked if, in the test voltages for the electrical design criteria, a short circuit in the magnet was considered. F. Rodriguez Mateos replied that the conditions would be presented later in the day. P. Fessia enquired if a study on the radiation effect on Kevlar was performed. A. Ballarino replied that this material was chosen since it is strong and light. In addition, she believes that this material is compatible with the radiation requirements, but she would recheck. P. Fessia added that the new DFHX concept is in its early stages regarding integration, and significant work should be performed.

Superconducting Bus Bars inside Cryostats – E. Todesco

E. Todesco presented the requirements of the superconducting bus bars, their layout and their design selection. He also presented the protection strategy of the bus bars and stated that the studies are being finalized. He concluded that a critical point is the protection of the MCBXFB bus bars that relies on the power converter crowbar. This subject is under discussion by the concerned teams.

N. Mitchell asked about the position of the voltage taps on the bus bars. E. Todesco stated that the layout would be shown in R. Denz's presentation and confirmed that all splices and bus bars would be monitored with redundant voltage taps.

N. Mitchell interrogated about the variation of the hot spot temperature between the bus bars (NbTi) and the magnets. E. Todesco stated that indeed the variation comes between the magnets and the bus bars, but the requirements on the variety of bus bars is consistent (between 100 K and 120 K). He added that this could be obtained with realistic design constraints on the bus bars.

Quench Protection Strategies – A. Verweij

A. Verweij presented the general strategy for superconducting elements quench protection and detection and for the related protection studies. Afterwards, he presented the quench protection strategies for the superconducting link, the current leads, the superconducting bus bars and the different magnets (including the hollow electron lens main magnets). He showed the expected hot spot temperature and the expected voltage to ground for the different circuits taking into account the worst realistic failure scenario.

H.J. Eckoldt asked about the variation between the SQUID and ROXIE software results. A. Verweij stated that ROXIE is a 2D software that is less reliable for magnets depending quench propagation (without active quench protection). However, it is very reliable and is validated with LHC results for circuits with active quench protection. He added that a third tool based on ANSYS 3D simulation software is being developed to this end.

P. Fessia asked about magnet poles ordering and its benefit versus the quality control that should be added during manufacturing. A. Verweij added that ordering of pole orders in one magnet could be necessary depending on the strand parameters variation (Cu/noCu ratio and RRR) and could reduce the simulated voltages of 200 V in the case of the 11T MBH. A. Verweij added that more simulations are planned on this subject. G. Ambrosio added that there is no showstopper to order the poles in the MQXFA magnets.

Regarding the worst case voltages and the electrical quality assurance, N. Mitchell asked if a short to ground inside a magnet is considered. F. Rodriguez Mateos informed that the conditions are explained case by case in his talk with the safety margins applied.

It was also recalled that the experimental data of the quench protection would be handled in separate talks on Tuesday 2019-09-10.

Quench Detection, related Hardware and Required Instrumentation - R. Denz

R. Denz presented the quench detection system and the related hardware with a conceptual design for HL-LHC (named UQDS). He also presented the firmware of the QDs and explained the deloyment and the tests in the superconducting magnets test facilities. He showed as well the signals from the 11T prototype magnet test and showed the impact of the flux jumps on the current dependant detection. He, then, showed the instrumentation and the measurement techniques of the superconducting link as well as the magnets (namely in the inner triplet circuit). He presented the triggering layout (inner triplet and 11T MBH) and showed that, in case of spurious firing a CLIQ system for instance, the beam abort takes less than 1 ms or around 11 turns of the team. This input is vital for the talk on the effects of protection equipment on the beam presented by D. Wollmann later.

A. Yamamoto asked about the location of the UQDS in the case of the 11T and the impact in regards to radiation doses. R. Denz replied that the UDQS will be placed in the excavations near the tunnel and the equipment will be radiation tolerant.

S. Gourlay asked if the new QDS has been tested on the 11T series. R. Denz confirmed that this was done in SM18 at CERN.

A. Yamamoto interrogated how the noise rejection is managed from measurement signals. R. Denz informed that the 128 kHz sampling time of the signals provide a very high bandwidth and filtering oppurunity. The bandwidth, filtering and the noise rejection would be adapted to the different systems (bus bars, magnets, cable in the link, etc.).

Regarding a question by A. Yamamoto on the single event failures of the UQDS, R. Renz confirmed that the system has been tested in radiation at PSI, and the firmware installed on the flash memory makes it radiation tolerant.

Quench Protection Hardware – D. Carrillo

The different subsystems composing the quench protection system other than the quench detectors are presented by D. Carrillo. Namely, cold diodes, quench heater power supplies, energy extraction systems and CLIQ units are shown. The relevant aspects required for a dependable quench protection are as well presented.

J.P. Burnet asked about the IEC standard used for the energy extraction systems based on vacuum switches. F. Rodriguez Mateos replied that this will be treated in the near future since the design is being finalized and has been proven to be technically reliable.

Regarding a question by H.J. Eckoldt on the time effectiveness of CLIQ for quench protection, F. Rodriguez Mateos confirmed that the magnet starts quenching in the first 10 milliseconds at nominal current. Therefore, the response is very fast.

N. Mitchell enquired on the resistance maximum temperature during discharges, and F. Rodriguez Mateos stated that the limit is 100 °C.

Concerning the energy extraction system technology, A. Yamamoto wondered if thyristor or other technologies were considered. F. Rodriguez Mateos informed that the IGBT technology was studied but was not retained due to the relatively high losses in semi-conductor switches. In addition, following a question by H.J. Eckoldt, F. Rodriguez Mateos informed that DC mechanical switches were also considered but the technology was not retained for HL-LHC due to the high maintenance. He confirmed that vacuum switches provide an advantage in terms of maintenance since no erosion is present and the speed of response.

F. Rodriguez Mateos confirmed that the vacuum switches are fully redundant (two switches in series) after a question by N. Mitchell.

Design for the Protection and Diagnostic Feeders of the HL-LHC Triplets - L.R. Williams

The design of the feeders serving the IFS CLIQ and k-mod systems to fulfil their thermo-electric, mechanical and cryogenic requirements were presented by L.R. Williams. The routing of the related feedthroughs and ancillary equipment for connection at their warm and cold ends were illustrated.

H.J Eckoldt requested the temperature boundary condition on the warm end. L.R. Williams stated that the limit is 288 K below which condensation would occur. N. Mitchell asked if an active heater can be used, L.R. Williams replied that, due to radiation and access limitations, it has been decided not to use active components.

J. Strait asked about the location of the presence of gas helium, and L.R. Williams informed that the gas helium is in contact with the feeders inside the cryostat.

A. Siemko interrogated on the difference between the temperature on the IFS pins level. L.R. Willimas replied that this is due to the difference of the sections of the pins (instrumentation pins or quench heater supplies pins). In addition, A. Siemko asked why the thermalization bloc was abandoned from the design. L.R. Williams responded that the thermalization is less effective for the HL-LHC design with respect to the LHC design for the 60 A and 120 A circuits.

J. Strait enquired if the heat collectors were integrated in the machine models, and asked about the natural convection possibilities. L.R. Williams informed that this is a point to work on in the upcoming weeks and stated that, since the integration space is confined, no natural convection is considered. This would make the design on the conservative side. P. Fessia added that the final design of the heat collectors should take into account the integration of the equipment around the feeders.

Contribution of Power Converters to the Protection of the Circuits - S. Yammine

The contribution of the power converters to the protection of the circuits was presented by S. Yammine. He presented the general considerations for the crowbar systems in the power converters. He described four case studies in the HL-LHC: the 11T trim circuit, the inner triplet circuit, the RCBX circuit with the MCBXFB and the superferric high order circuits. He presented the studies that have been done between WP6b and WP7 to ensure the protection of the circuits. He stated that the circuits have an appropriate protection strategy where the crowbar reduces the risk of triggering the quench protection system is several cases. This excludes, however, the RCBX circuit without the energy extraction which relies on the crowbar for the superconducting bus bar protection. Since the probability of a short circuit across the crowbar cannot be disregarded, the bus bar protection cannot be ensured in all cases. He stated that this subject is still under discussion to ensure a proper circuit protection. Afterwards, he presented the circuit disconnector boxes and their contribution to safety of personnel and systems.

H.J. Eckoldt and A. Yamamoto asked about the interlocks on the circuit disconnectors. S. Yammine informed that the disconnectors would rely on an interlock from a redundant current reading in the circuit, and on a padlock that requires a human intervention for energizing the motor of the disconnector.

L. Bottura enquired about the MTBF of the crowbars. Y. Thurel and S. Yammine replied that it would be estimated in the range of 5-10 years. However, tests should be performed to be sure of this value regarding the HL-LHC converter design.

D. De Luca asked about the status of the room temperature DC cables configuration. S. Yammine replied that with the new concept of the DFH in the URs the DC cables routing should be seen again.

H.J. Eckoldt interrogated on the reason behind not connecting the grounding to the midpoint of the energy extraction resistance as for the quadrupole corrector. S. Yammine replied that, as in LHC, it is preferred to connect the grounding to the power converter not to stress the measurement electronics and the EMC capacitors at every discharge. Therefore, the grounding stays at the power converter side except when it is required by the magnet to do otherwise.

Effects of Protection Equipment on the Beam and Reliability Studies for the Circuit Protection Systems - D. Wollmann

D. Wollmann presented the effects of the protection equipment spurious firing on the beam. In addition, he presented the reliability analysis for the circuit protection systems. He, first, showed the expected kicks from the spurious firing of the quench heaters in the different magnets and concluded that the connection of the quench heaters are made for a quadrupolar scheme. He, then, analysed the effect of a spurious firing of a CLIQ unit with two connections. He, then, concluded on the CLIQ connection that has the least effect in the beam where the beam reaches 1.5 sigma after 20 turns for a spurious firing in Q1 and after 16 turns for a spurious firing in Q2.

In regards to the reliability analysis of the circuit protection systems, D. Wollmann presented the ongoing activities in WP7 from the definition of the targets and the demonstration of the system designs to comply with the defined targets. These activities involve many magnet and equipment experts with dedicated mythologies and tools developed.

S. Feher asked if the quench heater power supplies are monitored. D. Wollmann replied postively and said that the quench heater power supplies are placed in the UR. Therefore, triggers linked to radiation is not considered. Therefore, a trigger of many power supplies is considered unrealistic.

J. Strait asked if different mechanisms were studied regarding the spurious triggering or other quench protection system effect on beam. D. Wollmann replied that all that was seen in the LHC and the scenarios that can be foreseen were analysed for HL-LHC. A. Apollonio added that, on the electronics level, an order of magnitude in failure occurrence is taken as a margin in the studies.

J. Strait added that every quench in HL-LHC represents a test of the quench protection system. D. Wollmann agreed and stated that, as in LHC, the machine will not be powered excpet all the circumstances of the quench or other failures are fully understood.

Integration Studies - M. Modena

M. Modena presented an overview on the HL-LHC new underground layout. In addition, he showed the integration of the HL-LHC technical systems related to magnet circuits in the new and old LHC technical galleries and the tunnel in points 1, 5 and 7. He reminded that the galleries for powering (URs) are intended to be accessible during operation of the machine.

A. Yamamoto enquired about the power converter location for Q4, Q5 and Q6. M. Modena replied that, as in LHC, they would be placed in the RRs.

H.J. Eckoldt asked about the major work that lies ahead for integration. M. Modena replied that the integration of the new concept of the feed boxes in the URs will be the most demanding in the future as well as the definition of the cable trays that connect the tunnel to the technical services.

H.J. Eckoldt also asked about the fire safety strategy in the URs and if fire extinguishers are present in the powering racks. M. Modena replied that the UR is divided in compartments each separated with safety anti-fire doors. He added that ventilation can extract smoke. The scheme and the boundary conditions have been validated by the safety team at CERN with appropriate studies undergone. P. Fessia also mentioned that fire extinguishers in the powering racks was not requested by the safety team, and additional safety studies are being done on the battery system of the inner triplet main power converter.

A. Yamamoto asked if the installation work would continue after LS2. M. Modena confirmed that access would be granted during machine operation to some HL-LHC galleries during RUN 3 since plugs will be added to isolate from the machine radiation.

Voltage Withstand Levels - F. Rodriguez Mateos

F. Rodriguez Mateos introduced the reason behind introducing electrical insulation tests and presented the strategy and the test sequence of the superconducting elements. Afterwards, he showed the reference values for the NbTi and Nb_3Sn magnets. He showed the impact of the non-uniform distribution of the strand parameters. Furthermore, he described the proposed insulation test at intermediate cryogenic temperature for the 11T MBH and the MQXF magnets. He emphasized that these tests represent the conditions at quench with the mentioned failures.

S. Gourlay asked if humidity was taken into account for imposing the test conditions. F. Rodriguez Mateos confirmed that in the relevant Engineering Specification documents, the conditions on humidity is defined.

P. Fessia emphasized that the magnet designer should receive the electrical insulation requirements. F. Rodriguez Mateos confirmed that these documents are written in collaboration with the magnet designers and are distributed to the concerned parties.

S. Gourlay interrogated about the test levels for the refurbished magnets, and F. Rodriguez Mateos and L. Rossi informed that the refurnished LHC magnets are retested at the same criteria as a new one after enough time following helium exposition. However, helium in Nb_3SN impregnated magnets is trapped in the magnet for a longer time.

A. Yamamoto asked about the test voltages between quench heater and ground. F. Rodriguez Mateos stated that these values could be also defined to the same criteria.

N. Mitchell asked why instead of applying intermediate tests, the Paschen's law is followed, and tests are performed at liquid helium with a higher temperature. F. Rodriguez Mateos replied that the voltages become very high and the limits of the test stations would be surpassed.

11T MBH: Electrical Integrity and Quench Protection Test Results - F. Savary

F. Savary presented the electrical tests required for the 11T MBH. Afterwards, he showed the insulation design of the cable, for the coil to ground and for the coil to quench heater. After recalling the quench parameters and strategy of the MBH, he showed the electrical tests performed on the models, prototypes and series magnets. He, also, showed different tests performed on model magnets to study the impact of thermal cycling, the impact of the proposed insulation test at intermediate temperature and the impact of extended MIITs test on the magnet insulation and performance. After discussing the variable thresholds for the magnet quench detection due to flux jumps, F. Savary explained the reasons behind the evolution from impregnated to external quench heaters in the design.

After a question by H.J. Eckoldt on the variation of the values between the recommended test voltages by the Magnet Circuit Forum and the levels applied to the models (1 kV), F. Savary informed that the limitation comes from the elevated instrumentation cables in the models. For the prototypes and the series magnets, the values determined in the Magnet Circuit Forum are applied.

Regarding the test at intermediate temperature, F. Rodriguez Mateos specified that helium was identified in the windings, and he stated that this proposed test is focused for the Nb_3Sn magnets with impregnated quench heaters (2 of the MBH series).

N. Michel added that the magnet design is evolving during the programme that leads to a hard position to evaluate the design versus the history of the evolution.

MQXF: Electrical Integrity and Quench Protection Test Results - G. Ambrosio

G. Ambrosio recalled the requirements and the targets of the MQXF magnet and showed the design linked electrical insulation of the magnet. He, also, recalled the test values for the MQXF magnet and stated that pole ordering is accepted by AUP to reduce the expected voltage development. He presented the test level at intermediate temperature that is proposed by the Magnet Circuit Forum. He presented the design validation tests of the quench protection strategy and showed the data analysis for the quench heaters insulation tests. He stated that the tests including the tests at intermediate temperatures qualify the MQXF for the HL-LHC requirements.

J. Strait asked if the quench heaters will remain impregnated in the MQXF or will be external as the 11T MBH. G. Ambrosio stated that the current design with impregnated quench heaters fulfil the requirements. In addition, he informed that the voltage levels of the 11T MBH are higher than in the case of inner triplet circuit, mainly due to the energy extraction system of the RB circuit.

P. Fessia asked if the test at intermediate temperature is beneficial. G. Ambrosio confirmed that it adds value to the tests and is accepted by the AUP. P. Fessia, also, enquired about the ordering technique of the magnet poles. P. Ferracin replied that this will be done with respect to classification of the poles by strand parameters. S. Gourlay questioned if this has no impact ordering due to mechanical or field quality constraints. P. Ferracin informed that there is no foreseen issue.

Regarding the voltages to ground, L. Rossi asked why Q1 and Q3 always see lower voltage to ground with respect to Q2a and Q2b independent of the warm diodes configuration. E. Ravaioli informed that, given the Q1 magnets are divided to two 4.2 m magnets, this has an impact on the simulations and leads to a lower voltage to ground.

L. Bottura stated that a complex phenomenon happens after exposure to helium of the magnets with impregnated quench heaters. This phenomenon should be understood with its impact on the long term reliability. On that note, G. Ambrosio informed that many tests were performed on the magnet that has seen the most thermal cycles and quenches and no continuous degradation is observed. He added that the magnet performance is established after some quenches and no further degradation can be recorded. In addition, the radiation effect on the insulation of the quench heaters is estimated to be negligible since the quench heaters are on the outer layer.

After a question by H.J. Eckoldt on the development plan, P. Ferracin stated that magnets will be tested to confirm the long term reliability. In parallel, other design variation would be studied like external quench heaters.

It was convened to have a focused discussion on the quench heaters positions and the impact on the magnet protection and insulation in a dedicated talk on Tuesday afternoon.

NbTi magnets: Electrical Integrity and Quench Protection Test Results - A. P. Foussat

A.P. Foussat presented the status of high voltage electrical tests campaign performed on HL-LHC NbTi models and prototypes (D1, D2, D2 correctors, inner triplet correctors and superferric high order correctors). The talk focused on electrical integrity and quench protection tests, which are appropriate to the qualification of the insulation system and the quench protection strategy established in A. Verweij's talk. He showed that no major issue is reported in these tests. After a question on the hot spot temperature limit of the MCBXF magnet, E. Todesco stated that the limit is increased to 300 K since it is relatively energetic corrector magnet. However, with the presented protection strategy the hot sport is limited to less than 200 K.

P. Fessia asked if the test voltages between bus bars takes into account the positive and negative energy extraction voltage. F. Rodriguez Mateos confirmed that this is considered for the sc link and for the bus bars tests. However, since the bus bars are connected to the magnets, the higher test voltage level is imposed.

Document Plan, Management of Change – S. Yammine

The Magnet Circuit Forum has created, collected and managed the documentation for the HL-LHC magnet circuits and related studies. S. Yammine presented the documentation plan for the HL-LHC magnet circuit and the strategy of the management of the change in accordance to the HL-LHC Project Documentation Plan. He showed the management of three types of documents: the Magnet Circuit Forum related documents, the HL-LHC project documents and the CERN official documentation on magnet circuits.

J. Strait asked which documents go to HL-LHC sharepoint and which documents go to EDMS. P. Fessia informed that the working documents go to sharepoint and when finalized they are uploaded to EDMS.

Regarding the approval of documents, A. Yamamoto asked if all documents are approved in TCC. O. Bruning stated that documents are presented at TCC for information in TCC, but EDMS is used for the approval by group leaders, work package leaders and the concerned people.

The HL-LHC Inner Triplet String - M. Bajko

M. Bajko presented the HL-LHC Inner Triplet string test at SM18. She started by presenting the motivation and the goals of the test and continued by showing the layout and the main components. She stated that the test would include the magnets from Q1 to D1 including all the correctors. She described the main steps of the string test from installation and interconnection to the hardware commissioning and the experimental programme. She presented as well the main components to test and the collective behaviour of the circuits (cross-talk between circuits, nested control, precision, failure scenarios verification, etc.).

After a question by A. Yamamoto about the thermal cycle, M. Bajko stated that the proposed test programme is to cool down the magnets to 1.9 K, then warm-up to room temperature and cool down again performing powering tests at cold. She stated that this scheme provides many inputs and is very beneficial for the collective learning.

S. Gourlay asked about the resources involved in the string test. M. Bajko replied that, in the time being, only limited resources are working on the project (mainly for planning, technical coordination and integration). For the installation, the different involved groups subscribed to this programme with allocated resources for installation and the test programme. She added that, even if an operator from the CERN Control Room is not foreseen to run the string test, expert engineers and physicists from the different groups are expected to provide the operation of the string test in collaboration with WP16.

J. Strait asked about the technical risk analysis of the string. M. Bajko informed that there are studies undergoing on the functional analysis and the interaction between systems. In addition, M. Bajko stated that a study in collaboration with WP7 has been done to identify the risk and mitigations of the string test on the machine. It was convened to present them in the special session in the afternoon.

J. Strait also asked about the differences about the machine configuration and the string installed in SM18. M. Bajko informed that the main difference regarding safety is that people are present in the SM18 hall during tests. Therefore, the personnel safety measures are different, and, in collaboration with the project safety office, a dedicated study will be performed. She added that the operation and calibration of the systems (cryogenics, magnets, power converters, etc.) would be identical or with minor differences to the machine configuration.

Safety Aspects - T. Otto

T. Otto presented the safety considerations for the HL-LHC magnet circuits. He started the presentation by showing the powering configuration of the LHC and the main differences between the LHC and the HL-LHC. He stated that HL-LHC underground for powering systems (UR) areas are accessible during machine operation. In his talk, he covers the risk of direct or indirect electrical contact and the electrical arcs in powering systems. He showed that the steps to achieve the electrical safety conformity and the standards followed for the project. He stated that a main component for the safety analysis is the battery system of the main inner triplet power converter. He, then, showed the safety workflow used for HL-LHC equipment with the resulting documentation.

P. Fessia stated that the Major Safety Implications (MSI) on the cryogenics of the cold systems are not presented. T. Otto informed that the study is undergoing and will be ready in the upcoming weeks. He added that the electrical feed boxes in the UR contain gaseous helium which makes this less dangerous with respect to superfluid helium. However, he stated that, since the cold powering design is not finalized, assumptions and margins should be taken into account. After O. Bruning recalling that the access to the UR must be maintained during machine operation, T. Otto informed that the self-rescue mask will be obligatory for fire safety and since safety exits are ensured by passing in the tunnel.

Concerning the risk of the helium from the tunnel arriving to the powering galleries, T. Otto confirmed that seals will be present as in the LHC (i.e. CMS powering cavern – USC55) to prevent from this situation.

D. De Luca asked if failure in arc is analysed. T. Otto said that this will be analysed with TE-EPC to impose the proper distances and enclosures.

M. Bajko informed that the same documentation done for HL-LHC equipment would be used for the string test. In addition, T. Otto confirmed that the string test would also help testing the safety procedures for the machine.

Discussion on Specific Questions by the Panel

Risk Analysis of the String Systems - M. Bajko

M. Bajko presented the study done on the impact of the string on the hardware commissioning of HL-LHC. She listed several activities foreseen in the string test but that can be absorbed by the hardware commissioning in the machine. She listed, as well, issues that can possibly last beyond the hardware commissioning and where the string test is very important. She informed that the most prominent items for the string test is the cross talk between circuits, the magnet protection configurations and setting, the nested control and the alignment system.

S. Gourlay estimated that quenches in the superconducting link means that there is a more critical issue than the estimated downtime since it is designed to be very robust and with operation margin. However, M. Bajko stated that the unforeseen issues (unknown unknowns) are an important part of the validation. A. Yamamoto added that testing the cross talk between the circuits and the sustainability of the cold powering systems in the realistic environment is very important.

Regarding planning, S. Gourlay and N. Mitchell asked if the programme is reduced to 9 months, would it still be interesting to carry on with the string test. M. Bajko replied that the full programme including a thermal cycle would not be carried out and there is already no contingency included in the planning. A. Yamamoto added that a thermal cycle is a priority and maybe less quenches at high current could be foreseen.

Table with Voltages and Temperatures on QXF Magnets – E. Ravaioli

E. Ravaioli presented the equivalent circuits of the MQXFA and MQXFB magnets and showed the simulated voltages to ground. He showed that with ordering of the poles to respect a given strand parameter variation the maximum voltage to ground is 657 V in the case of an MQXFB magnet. He informed that the voltage to ground variation between MQXFA and MQXFB is 1.7 which is related to the magnetic length ratio. Afterwards, he showed the simulation curves that lead to the presented values.

S. Gourlay asked about the considered variation of the RRR and the copper to non-copper ratio of the strands. E. Ravaioli stated that these were provided by TE-MSC at CERN and the RRR is within 150-250 and the Copper ratio is between 1.15 and 1.25.

H.J. Eckoldt asked about the validation of the software. E. Ravaioli answered that the Steam-LEDET software was validated with data from tests on the MQXF.

Voltage Withstand Levels and Quench heater Position for QXF and 11T MBH – F. Savary and G. Ambrosio

F. Savary presented the issues encountered with the quench heaters insulation during the manufacturing of the magnets, and the plans for the new external quench heaters. Whereas, G.

Ambrosio showed the tests performed on the MQXF magnets (models and prototypes) and the validation with the tests at an intermediate, cryogenic temperatures.

The panel concluded that the proposed insulation of the MQXF magnets and the 11T is very similar. However, the choice of external quench heaters for the 11T MBH stems from the higher expected voltages and, therefore, higher test voltages.

A. Yamamoto added that the proposed insulation for the 11T MBH with external quench heaters becomes very close to the MB insulation design.

F. Rodriguez Mateos added that the intermediary test adds confidence to the magnets before installation in the machine. A. Siemko added that this test contributes to the proof of long term reliability of the magnets.

F. Savary stated that the plan today for the 11T MBH is to produce and install two MBH magnets with impregnated quench heaters (series 1 and series 2) and two MBH magnets with external quench heaters (series 3 and series 4). Two additional MBH magnets with external quench heaters will be produced for spares.

Regarding the tests on the MQXF, G. Ambrosio stated that there is not enough evidence to change the baseline to external quench heaters in the case of the MQXF, and the electrical QA is followed as recommended by the Magnet Circuit Forum. He added that since the quench heaters are on the outer layer, a dose 5 MGy is expected and no issue is foreseen regarding the impact of radiation on the insulation of the quench heaters.

Splices in HL-LHC Cryostats - H. Prin

H. Prin showed the different splices in the HL-LHC cryostats and the corresponding procedures. He showed the 11T trim joints, the CLIQ joints, the k-mod connections and the trim connections in the inner triplet main circuits.

A. Yamamoto commented that the procedures seem to be well established. H. Prin added that many of the procedures and designs are identical to LHC cases.

N. Mitchell asked about insulation in the case of the k-mod connections. H. Prin replied that a box around the joints will be added.

H. Prin added that there might be minor differences between the MQXFA and the MQXFB but the principle is the same. The difference is mainly the orientation of connection of the cables. He also stated that in the case of the trims in the inner triplet, the superconductors will not have contact and the current would pass through the copper.

J. Strait asked if the splice resistance is measured in the quality control in the tunnel. H. Prin confirmed and stated that the development of the inner triplet trim splices is not on the critical path since the first implementaion would be needed for the string test.

Reliability of the Complete Inner Triplet Circuit Protection - A. Apollonio

A. Apollonio presented the reliability analysis of the complete inner triplet circuit protection. He stated that the design target is 10% probability of damaging a triplet in 100 years. He showed the models used in the reliability analysis.

H.J. Eckoldt asked if reliability curves are introduced to the models. A. Apollonio stated that, in the time being, constant values are introduced, but other effects like ageing for instance could be added in the models.

After a question by J. Strait on the feedback of the reliability models to the design of equipment, A. Apollonio and F. Rodriguez Mateos confirmed that many system designs (like CLIQ) have input from the reliability study.

A. Apollonio informed that benchmarking is done by experience from the machine if data exist. If not, datasheets of the components are used. In the case of missing the previous data, information from standards are used in the models.

Feedback from LHC and MDs done with Respect to Effects to Beam by Misfiring of Protection Elements - D. Wollmann

D. Wollmann reported on the experience with quench protection equipment effects of the beam in LHC. He showed the orbit oscillation during an LHC dipole quench. He showed as well the dedicated experiments done in the machine and the expected kicks from HL-LHC magnets. He, then, showed the proposed mitigations regarding quench heaters and CLIQ connections in the magnets.

After a question by A. Yamamoto, D. Wollmann confirmed that the quench heater connections should provide a quadrupolar or higher field.

J. Strait asked the impact on beam if one QH circuit is not fired (as considered in the quench protection failure scenario). D. Wollmann replied that this might have a dipolar contribution but the baseline is still to dump the beam before activating the quench protection system.

Security of Firmware in Quench Detection and Potential Protection Implications - R. Denz

R. Denz presented the quench detection system firmware security and the method that ensure maximum reliability. He showed the methodology of the development and the verification of the firmware.

S. Gourlay asked about the manuals related to the quench detection systems. R. Denz said that the people testing the systems (different from the developing team) use the written manuals and give feedback. Nevertheless, the information about the development remains near the firmware code and could be used in the future for understanding the code. R. Denz confirmed that the coding language for the firmware uses basic VHDL without add-ons linked to specific FPGAs. Therefore, any future FPGA could be used in the application. This provides a solution for obsolete FPGAs and components.