Final: 16/05/27

Report from the Review Panel for the Review of the 11T Dipoles at Collimator Section for the HL-LHC

6-8 April, 2016, CERN Geneva

Review Panel Members
Giorgio Apollinari (Fermilab), Arnaud Devred (ITER), Pasquale Fabbricatore (INFN),
Joe Minervini (MIT), Pierre Vedrine (CEA), and Akira Yamamoto (KEK-CERN, Chair)

1. Introduction

HL-LHC is in the final stage of design and prototyping. All technologies for the hardware upgrade must be fully proven by beginning of 2017.

This review covers the 11T dipole, planned to substitute the LHC dipole cryo-magnets in the Dispersion Suppressor, with a new unit producing the same integrated field, requiring a bore field in the range of 11 T, and an integrated by-pass for a collimator (see Appendix 1 and 2).

Previous technical reviews addressed the engineering concepts, and cost and schedule (see Appendix 3).

This review addresses:

- Magnet design status, with special attention to the cold mass, its cryostat and electrical, hydraulic, mechanical, vacuum interfaces and integration in the LHC continuous cryostat and LHC arc circuit;
- By-pass and collimator design;
- Results of model magnets;
- Status of prototype magnets;
- Conductor performance, procurement status and plans;
- Status of production tooling, finalization of design and procurement;
- Components procurement, status and plans;
- Test plan, QA/QC, and safety aspects;
- Production schedule and global plan to installation (including constraints given by LS2).

Questions/charges given to the panel are summarized as follows:

Overview

- *Is the overall plan for the 11T dipoles at collimator section clear, realistic and coherent with the whole HL-LHC project? Does it satisfy the needs?*
- *Is the plan matching the request from collimation?*
- *Are the recommendations from the previous review adequately followed-up?*

Model magnet work

- *Was the acquired experience with the models well fed into the prototype/series design?*
- *Have all useful tests been carried out? If not, which ones would you recommend?*
- *Have the tests results been sufficiently analyzed and understood? If not, do you recommend further analysis?*

Prototype / Series magnet

- *Is the development of the design (superconductor, collared coil, cold mass, cryostat, etc.) appropriate with respect to the overall project (in terms of quality, schedule, resources)? If not, what are the critical areas?*
- *Is the development of the tooling appropriate wrt the overall project (in terms of capacity, quality, schedule, resources, margins, etc.)?*
- *Are all procurement aspects (superconductor, collared coil, cold mass, cryostat, etc.) including QA/QC in line with the needs ? If not, what is missing or should be reinforced?*
- *Is the protection scheme presented sufficiently robust to be compatible with the operation constraints? If not, what is missing or should be developed or modified ?*
- *Is the powering scheme presented adequate for the operation of the 11 T in the LHC arcs? If not, what are the areas to improve?*
- *Is the test plan (throughout production and acceptance tests) sufficiently developed? If not, which critical tests are missing?*
- *Is the production strategy at a level of maturity stage corresponding to the global project?*

As a summarizing question

- *The results obtained so far and a plan for the project were presented. Have you identified missing topics that would jeopardize the 11T dipoles at collimator section and prevent from installing two 11T assemblies during LS2?*
- *Is the plan to meet the challenges realistic? Is the inherent level of risk acceptable?*

2. Report from the Review Panel

2.1. Executive Summary

The 3nd international review of the "HL-LHC 11 T dipoles at Collimator Section" was held at CERN, 6-8th April, 2016.

The review panel (committee) received ~30 reports on the recent technical progress and the future project plan to meet the requirement for two pairs of 11 Tesla dipole magnets to be ready in series operation with LHC lattice main dipoles, after the LS2 completion in 2020.

The committee summarizes our advice as follows:

After visiting the site for the model/prototype-work activities, the committee has been very impressed with the significant technical progress, initiated at Fermilab in the early stage, and then extended by CERN in the past several years.

Reaching the maximum field above 12 T and stable operation at 11T with the model magnet is a great milestone achievement for the HL-LHC project. The committee recognizes that the Nb_3Sn magnet technology has matured and is now practical for applications in specific areas where higher magnetic fields above 10 T are critically required.

Success of the 11T project will set the stage for further Nb_3Sn applications in energy-frontier hadron accelerators.

The project needs to move quickly into the LS2 construction stage after the ongoing prototype work with full-length coil windings, magnet assembly, and demonstrated performance. No time remains for any major design changes.

The committee is pleased with the plan for the production magnets to be tested to a level having sufficient margin (> 105 %) in terms of the nominal operation current, with confirmation of the mechanical stability/margin before installation into the tunnel. It may also minimize the number of re-training quenches after periodic thermal cycling in steady state operation in the tunnel.

The committee is pleased to recognize that the magnet interface to the collimator has been well established.

The project time scale for the first set of 11 T dipoles is still very challenging for them to be ready in the LHC tunnel by 2020, even with the assumption of no failures in the fabrication process of 10 units (8 + 2 spares) over the course of ~3 years.

For the LS3 program, the committee endorses the development of a 2nd strand supplier for LHC upgrade magnets. The committee recommends to move expeditiously with the manufacture of dipole model magnets with the new PIT strand layout, cable design, and magnet cross-section. Nevertheless, design changes with respect to LS2 magnets should be minimized. It is essential to define milestones and decision points for the PIT strand adoption and the change of cross-section for LS3.

The committee encourages development and update of the manufacturing plan, including tooling usage, and under various assumptions for involvement of industry, for all combined activities required by LS3 (11 T dipoles, MQXF, and other projects).

Several options for industry involvement in LS2 and LS3 were presented, and the committee encourages further development and integration of these capabilities into the project plan. This strategy, however, should not delay the construction schedule. Full production capability should be maintained at CERN.

The committee congratulates the great achievements of the team in the development of the 11T dipole with Nb_3Sn technology, reflecting the experiences and expertise of both US and CERN laboratories. We are also very pleased to see fresh efforts and continuity provided by much younger generation promising the future. However, we urge the magnet group to provide adequate supervision and training to ensure an efficient transfer of competence.

2.2. Review for the Model Magnet Work

***Questions**: Was the acquired experience with the models well fed into the prototype/series design?*

Response (finding, comments, and recommendations) from the committee:

- The committee has been much impressed with the progress since the previous review, in Dec., 2014.
- The model magnet work was very useful in developing different aspects of the fabrication processes, which led to the successful tests of the 2-in-1, 2m long dipole model.
- 5 model coils were built and tested, with 4 of them operated in magnets that passed nominal

and ultimate currents. The stability was demonstrated at sufficiently high currents.

- The committee recognizes the handsome payback from the design optimization with the "insertable pole" and "pole loading" concept in the 11 T dipole mechanical design.
- Embedded outer quench protection heaters are performing as expected.
- Field quality issues appear manageable for the series magnets.
- N*on-critical* issues remaining are the delay to quench in low field areas and understanding the difference with FNAL data regarding decay & snapback.

Questions: *Have all useful tests been carried out? If not, which ones would you recommend?*

Response from the committee:

- No other model coils are needed for LS2 design.
- Many of the tests and procedures recommended from the previous review were carried out.
- The committee recommends following tests /studies to be done:
  - Check for dry areas and voids of impregnated model/dummy cols. On the dummy copper model, make several cross-section cuts of the coils near both ends and the middle to investigate if the changes to the resin header method for impregnation really resulted in good distribution of the epoxy.
  - Take at least one of the Nb_3Sn model coils that was tested to ~11T or more and make several cross-sections to see if the effects of operation under heavy Lorentz load and stresses have resulted in any visible signs of internal damage, motion, voids, cracks, distortions, or displacements.
  - Perform compression tests on actual Nb_3Sn coil cross-sections to determine more accurately the coil modulus in order to improve the mechanical analysis.
  - Do paper studies on insulation braiding and compares with QXF results in order to elucidate observations on coil wedges gaps after reaction.

Questions: *Have the tests results been sufficiently analyzed and understood? If not, do you recommend further analysis?*

Response from the committee:

- The committee recommends to continue analysis of the quench data to determine why quench initiation in the low field region begins increasing later in time from the high field quench initiation when the operating current is reduced.

2.3. Review for Prototype/series Magnet Plan

Questions: *Is the development of the design (superconductor, collared coil, cold mass, cryostat,….) appropriate with respect to the overall project (in terms of quality, schedule, resources)? If not, what are the critical areas?*

Response from the committee:

- The design based on RRP conductor is at the appropriate stage of development to transition expeditiously to prototype/series production.
- We have been impressed by the quality of preparation for all production-related activities: procurement of parts, procurement of superconductor, procurement and commissioning of tooling, establishment of procedures, QA/QC, etc.
- The committee recommends to assess the PED and the impact on the helium vessel design, materials specification, and test procedure as soon as possible.

Question: *Is the development of the tooling appropriate with respect to the overall project (in terms of capacity, quality, schedule, resources, margins, etc.)?*

Response from the committee:

- Tooling for winding, curing, reaction heat treatment and collaring has been validated. More work is still needed for the impregnation station and welding press.
- Compatibility of the materials for the heat treatment mould should be reviewed. The present use of austenitic steel is questionable.
- In the present situation, a potential bottleneck seems to be identified, especially after the "LS2 Production", in the impregnation equipment shared by 11T and QXF coil manufacturing for LS3.
- Manufacturing plan for cable production was presented and appears credible. Backup solutions should be investigated with the US partner.
- No coil and magnet "Manufacturing Plan" with expected "tooling occupancy" was presented. Also, there is obviously space to improve "Production Rates" by duplicating some inexpensive tooling, such as impregnation molds, curing setups or winding support.
- The impression is that the 11T production will not have a major conflict for resources at the beginning (production for LS2) but will have to be coordinated with MQXF and other magnets production later in the preparation for LS3.
- In general, when assessing "Production" in future reviews, it would be beneficial to have integrated "production plans" between 11T, MQXF and other magnets, especially on items completely under CERN control (SM18 testing, etc.)
- When the industry participation has been decided, their role and resources should be integrated into the production plans.

Question: *Are all procurement aspects (superconductor, collared coil, cold mass, cryostat,….) including QA/QC in line with the needs ? If not, what is missing or should be reinforced ?*

Response from the committee:

- Yes, especially for LS2 magnets and RRP strand. No, for PIT strand and changed coil cross-section for LS3 magnets.
- Proceed with the procurement of RRP strands for LS2 and LS3 and proceed with the production of cables and LS2 magnets based on the present design.
- It is desirable to maintain 2 strand suppliers and to continue the development of PIT strands for Hi-Lumi LHC upgrade magnets.
- It is essential to define milestones and decision points for the PIT strand adoption and the change of cross-section for LS3. Design changes with respect to LS2 magnets should be minimized.
- QA/QC plans are well under development. QC measurements on strand could benefit from involvement of other organizations, thereby allowing CERN to concentrate on benchmarking and specialty measurements.

Questions*: Is the protection scheme presented sufficiently robust to be compatible with the operation constraints? If not, what is missing or should be developed or modified ?*

Response from the committee:

- The protection system appears to be well developed. The system relies on outer layer quench protection heaters.
- Improvements in detection time and dump time might be sufficient, but the committee recommends continued analysis and model development of interlayer heater in case it is found to be required for sufficient hot spot temperature margin. Nevertheless, decision of

implementation of interlayer QP heaters in production magnets should be very carefully assessed for its implication on the basic magnet design.

Questions: *Is the powering scheme presented adequate for the operation of the 11 T in the LHC arc? If not, what are the areas to improve ?*

Response from the committee:

- The committee recommends to study the possibility of Trim coil circuit test at SM18. In particular, the powering system in SM18 should be representative of operating conditions in the tunnel.

Questions: *Is the test plan (throughout production and acceptance tests) sufficiently developed? If not, which critical tests are missing ?*

Response from the committee:

- In general, yes. Plans for production and tests are well developed, including a "system test" with 2 magnets and bypass cryostat test in SM18
- Plans/schedules for testing should be developed for 11T, QXF and other magnets testing. SM18 hardware capacity is expected to be more than sufficient to support all magnet testing.

Question*: Is the production strategy in a maturity stage corresponding to the global project ?*

Response from the committee:

- For LS2 and RRP the production strategy is approaching maturity. However, since the schedule is "success-oriented", the committee suggests to consider anticipating LS2 series production of coils before completion of the prototype cold test.
- For LS2 and RRP production strategy, the committee endorses the present plan of executing production on CERN premises.
- The production strategy for LS3 is still at a development stage
- Several options involvement of industry in LS2 and LS3 were presented, and the committee encourages further involvement od industry in LS2. development and integration of these capabilities into the project plan. This strategy, however, should not delay the construction schedule. Full production capability should be maintained at CERN.

2.4. Summarizing question

Questions*: The results obtained so far and a plan for the project were presented. Have you identified missing topics that would jeopardize the 11T dipoles at collimator section and prevent from installing two 11T assemblies during LS2 ?*

Is the plan allowing to meet the challenges realistic ? Is the inherent level of risk acceptable ?

Response from the committee:

- The risks and mitigation strategies presented by the WP Leader in the closed session appear well thought-out and reasonable.
- In general, the level of risk is small in transitioning the project to "prototype execution" and then "construction" for LS2 given the successful model program based on "generation 1 cable" and the RRP superconductor.
- A competent crew is in place for all activities (magnets production, cryostat production, powering and protection schemes, QA/QC, etc.) and this insures a low risk for the LS2

production.

- The introduction of a "generation 2 cable" and PIT superconductor (and subsequent design change) introduces an element of risk for LS3 production that needs to be addressed immediately with an aggressive model program.

3. General Remark

The 3nd international review of the "HL-LHC 11 T dipoles at Collimator Section" was held at CERN, 6-8th April, 2016.

The review panel (committee) received 29 reports on the recent technical progress and the future project plan to meet the requirement for two pairs of 11 Tesla dipole magnets to be ready in series operation with LHC lattice main dipoles, after the LS2 completion in 2020.

After visiting the site for the model/prototype-work activities, the committee has been very impressed with the significant technical progress, initiated at Fermilab in the early stage, and then extended by CERN in the past several years.

Reaching the maximum field above 12 T and stable operation at 11T with the model magnet is a great milestone achievement for the HL-LHC project. The committee recognizes that the Nb_3Sn magnet technology has matured and is now practical for applications in specific areas where higher magnetic fields above 10 T are critically required.

The project needs to move quickly into the LS2 construction stage after the ongoing prototype work with full-length coil windings, magnet assembly, and demonstrated performance. No time remains for any major design changes.

The committee encourages development and update of the manufacturing plan, including tooling usage, and under various assumptions for industry involvement, for all combined activities required by LS3 (11 T dipoles, MQXF, and other projects).

The committee congratulates the great achievements of the team in the development of the 11T dipole with Nb_3Sn technology, reflecting the experiences and expertise of both US and CERN laboratories. We are also very pleased to see fresh efforts and continuity provided by much younger generation promising the future, but recommend that adequate attention be given to mentoring and supervision.

Acknowledgments:

We wish to thank all members for his/her effort involved in the HL-LHC 11T dipole project, and to contribute to the review. Congratulations for the successful review!

References:

Overview:
https://indico.cern.ch/event/493351/overview

Presentation Indico page:
https://indico.cern.ch/event/493351/other-view?view=standard

Appendices:

Appendix 1

Review Panel Members and relevant persons:

- Giorgio Apollinari (Fermilab),
- Arnaud Devred (ITER),
- Pasquale Fabbricatore (INFN),
- Joe Minervini (MIT),
- Pierre Vedrine (CEA).
- Akira Yamamoto (KEK-CERN, Chair),

- *Jean-Philippe Tock (link person)*

Appendix 2

The review meeting agenda is as follows:

4/6	Subjects	*Convener*/Speaker
8:30	Closed Session at Prevessin site (B774-R-013)	*A. Yamamoto*
9:00	Session 1	
	Welcome address	*Luca BOTTURA*
	Requests from Collimation	*Stefano REDAELLI*
	Introduction and new 11 T plan in HL-LHC	*Frederic SAVARY*
	Cryo-assembly and by-pass cryostat design	*Delio DUARTE RAMOS*
	Coil winding and collaring	*David SMEKENS*
	Cold mass assembly design	*Herve PRIN*
	Magnet powering and operation requirements	*Samer YAMMINE*
14:00	Session 2	
	Model magnet test results and analysis at FNAL	*Alexander ZLOBIN*
	CERN superconductor and cable design performance	*Bernardo BORDIN*
	Model magnet production and plan	*Juan Carlos PEREZ*
	Model magnet test results and analysis - Quench performance vs mechanics and operation requirements	*Gerard WILLERIN*
	Model magnet test results and analysis - Protection and operation requirements	*Susana IZQUIERDO BERMUDEZ*
	Model magnet test results and analysis - Magnetic measurements and operation requirements	*Lucio FISCARELLI*
4/7		
8:30	Closed Session at BE Auditorium , Meyrin	*A. Yamamoto*
9:00	Session 3	
	Magnet production : agenda of the day	*Frederic SAVARY*
	Safety and codes	*Thomas OTTO*
	11T QA	*Rosario PRINCIPE*
	Superconductor production plan, QA/QC	*Bernardo BORDINI*
	SC cable production plan, QA/QC	*Jerome FLEITER*
	Collared coil procurement, status and plan, QA/QC	*David SMEKENS*

	Cold mass procurement, status and plan, QA/QC	*Herve PRIN*
	Quality control tests throughout production – Factory acceptance tests	*Arnaud Pascal FOUSSAT*
14:00	Session 4	
	Cryostat procurement, status and plan, QA/QC	*Delio DUARTE RAMOS*
	Vacuum and cryogenics systems procurement : status and plan, QA/QC	*Cedric GARION*
	Powering and other systems procurement : status and plan, QA/QC	*Hugues THIESEN*
	Final acceptance tests – test bench readiness	*Gerard WILLERING*
	New cross-section and its rationale	*Emelie Kristina NILSSON*
	Feedback on the recommendations from the previous review	*Frederic SAVARY et al*
	Tooling status	*Friedrich LACKNER*
4/8		
8:30	Closed Session at BE Auditorium , Meyrin	*A. Yamamoto*
9:00	Session 5 Restricted Session	
	Magnet procudction strategy (restricted)	*Frederic SAVARY*
	Q & A Session	
	Visit Large Magnet Facility	
14:00	Session 6	
	Panel Closed session	
16:30	Close-out Session	

Appendix 3:

A group photo.

Appendix 4

Executive Summary from the previous review held at CERN on 8-10 December.

The 2nd international review of the "HL-LHC 11 T dipoles at Collimator Section" was held at CERN, 8–10th December, 2014.

The committee received 17 reports on the recent technical progress and the future project plan to meet the requirement for the 11 Tesla dipole magnets to be ready for steady operation, harmonized with the LHC lattice main dipoles, after the LS2 completion in 2019. The committee summarizes our advice as follows:

- The committee has been very impressed with the significant technical progress, initially at Fermilab in the early stage, and then extended by CERN in the past several years. The committee recognizes that the Nb_3Sn magnet technology has matured and is now practical for applications in specific areas where higher magnetic fields above 10 T are critically required.

- The goal of the 11 T Dipole project is to to realize the successful, stable operation of 11 T dipoles in the LHC accelerator by 2019, after LS2, as a pioneering application of the Nb_3Sn magnet in the HL-LHC project. Success of the 11T project will set the stage for further Nb_3Sn applications in energy-frontier hadron accelerators.

- The project needs to move quickly into the construction stage after completion of the model magnet and prototype phases with practice coil windings, magnet assembly, and demonstrated performance. Therefore little time remains for any major design changes, except for some fine-tuning of superconducting cable parameters and the peak field design in order to improve the operating margin by a few percent along the load line.

- The production magnets should be tested to a level of ≥105 % in terms of the nominal operation current, with confirmation of the mechanical stability/margin to greater than 10%, before installing the magnet into the tunnel. Such testing also contributes to understanding the number of re-training quenches required after periodic thermal cycling.

- The committee advises to optimize the magnet length in balance with the minimum acceptable collimator length. A high-level judgment and agreement between the magnet and collimator groups will be required to achieve this optimized balance.

- The committee encourages further cooperation between CERN and Fermilab, to reflect the experiences and expertise of both laboratories, particularly for the coming prototype work at CERN. We suggest an internal technical review within the collaboration, to maximize the exchange of information and experience.

- The project time scale is very challenging for the 11 T dipoles to be ready in the LHC tunnel by 2019, even with the assumption of no failures in the fabrication process of 20 coils over the course of 3 years. A more detailed project plan and internal review will be inevitably required, and priority given such that experienced personnel, facilities and components are available to keep the project efficiently progressing.