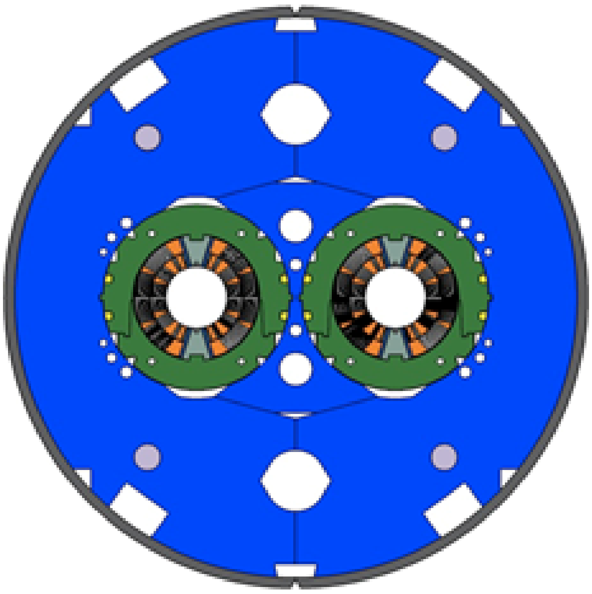
Report of the 2nd International Review of the HL-LHC 11 T Dipoles at Collimator Section

Review held at CERN, 8-10, December 2014

The 2nd International Review Committee:

Joe Minervini (MIT, Co-Chair), Giorgio Apollinari (Fermilab),
*Jim Kerby (ANL), Shlomo Caspi (LBNL), Arnaud Devred (ITER) **
Akira Yamamoto (KEK-CERN, Chair)

FINAL: 2015-02-04



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Executive Summary

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.

1. Introduction

The HL-LHC project is entering the final stage of design and model work, and all technologies for the hardware upgrade must be fully proven by the end of 2016.

11 T dipole magnets are to be installed into the LHC collimator sections, to provide reasonable space for the collimators in the dispersion suppressor (DS) regions, as part of the LHC continuous cryostat. These magnets will be the first high field magnets to be installed into the LHC accelerator operating above 10 T, by using Nb_3Sn superconductor,.

The first two sets of full 15 m long complete magnet assemblies must be installed in 2019 for improved collimation allowing increased collisions of ions at P2 of the LHC.

The HL-LHC Project Leader, Lucio Rossi, and the CERN TE-MSC Group Leader, Luca Bottura, called an International Review. The committee was charged to review the design and the construction plan of the 11 T dipoles, assessing the results of the initial R&D phase in view of the actual needs and targets for the machine, and assessing the proposed prototyping and construction phases to meet the LHC needs.

2. Charges given to the External Review Committee

The charges given to the External Review Committee are summarized in the following table.

Charge	Content
1	To review the basic design of the 11 T dipole, taking into account magnetic, mechanical and thermal operating conditions in the LHC P2: • Is the design meeting the targets with sufficient margin? • Does the experience of the first R&D phase at Fermilab and CERN (and of ten years of LARP & USA magnet basic programs) support the chosen specifications and the feasibility of meeting them with adequate margin?
2	Is the engineering design including the 3D interfaces to other systems, namely the cold-warm-cold by-pass lodging the collimation system, sufficiently developed to assess that there be no show stoppers in the construction of the magnetic part, the cold mass assembly, the cryostating, and the installation and integration in the machine? • Is the protection and circuit integration sufficiently analysed?

3	Is the final design taking stock of the best features demonstrated in the two development lines, i.e. FNAL and CERN?
4	*Are the design and manufacturing plans sufficiently well developed to engage in the upcoming significant procurements, i.e. Nb_3Sn strand and cable procurement and production, and magnet components procurement (collars, yoke, shells, etc.)?*
5	Is the plan for models and prototypes well thought? Is the preliminary construction plan credible?
6	Are the design and manufacturing plans sufficiently well developed to engage in the upcoming significant procurements, i.e. Nb3Sn strand and cable procurement and production, and magnet components procurement (collars, yoke, shells, etc.)?

3. Findings, Comments, and Recommendations from the Review Committee

Charge 1:

To review the basic design of the 11 T dipole, taking into account magnetic, mechanical and thermal operating conditions in the LHC P2:

- *Is the design meeting the targets with sufficient margin?*
- *Does the experience of the first R&D phase at Fermilab and CERN (and of ten years of LARP & USA magnet basic programs) support the chosen specifications and the feasibility of meeting them with adequate margin?*

Findings and Comments:

- No, the margin is not sufficient, but only at the edge of the acceptable range.
- Previous experiences from the first R&D phase are reflected, but there is still room for improvement.
- The current design margin along the LL at the nominal bore field of 11. 21 Tesla is 81.9 % with the full iron yoke, and it could be reduced to 80.6 % by modifying each end of the magnet to be 20mm longer and use a non-magnetic yoke. This extra 20mm length must be negotiated with the collimator team.
- The R&D targets are not yet sufficiently met either at FNAL (better) or at CERN. Quenches occurring in the CERN model are clearly indicating some weak spot in the mechanical assembly.
- Various design choices have been made, but they were not clearly explained in the talks including the choice of the island material, the pole piece 2D design, the transition region design mating the 2D and end regions, the choice of quench heater location, the allowable compressive stress in the coil during manufacture, etc.

Recommendations:

- Keep the core magnet design, but increase the operation margin.
- Decrease the SC LL ratio to be close to 80 %. It should be possible by using non-magnetic yoke at the ends.

- Verify the magnet operational margin with the excitation up to B-bore ~ 12 T (to demonstrate ≥105 % excitation of the nominal current, verifying the mechanical margin and training the magnet, including demonstration of thermal cycling memory, before installation into the tunnel.

Charge 2:

Is the engineering design including the 3D interfaces to other systems, namely the cold-warm-cold by-pass lodging the collimation system, sufficiently developed to assess that there be no show stoppers in the construction of the magnetic part, the cold mass assembly, the cryostating, and the installation and integration in the machine?

- *Is the protection and circuit integration sufficiently analysed?*

Findings and Comments:

- No specific presentation was made in terms of this question except for the general powering system.
- No major show-stopper is identified with the cryogenic and electrical integration.
- Encourage use of a same/similar scheme of the protection as the LHC-dipole and interconnect.

Recommendations:

- We urge the cryostat group to converge quickly on a design defining the envelopes for both magnets and collimators.

Charge 3:

Is the final design taking stock of the best features demonstrated in the two development lines, i.e. FNAL and CERN?

Findings and Comments:

- No, apparently not on mechanical structure.
- Yes, on many other elements in coil fabrication, conductor, etc.

- Although the review focused mainly on the CERN design, test results of both CERN and FNAL coils showed similar training and mechanical issues. In particular the CERN presentation of strain gauge measurements showed coil separation from the pole, a clear indication of lack of pre-stress. The use of collars requires an excess of initial pre-stress to compensate for spring back. The higher modulus of the impregnated Nb_3Sn coils in combination with high Lorentz forces and the coil sensitivity to stress/strain makes the use of collars difficult. Integrating the islands of both layers into the coils (as it was done by FNAL) and not removing them to be partially replaced with the collars "nose" is a step in the right direction but likely not sufficient.

- To overcome such difficulties the CERN 11T team would greatly benefit from an internal review using CERN existing expertise such as the QXF team and others who are working on structural issues. The team may have to meet several times before concluding how to proceed. The need is urgent and critical to the success of the 11 T dipole. Based on their recommendation and guidance a decision should be made on how the final design and especially how the assembly should take place.

- There is an opinion that a more radical change to the structure by introducing "keys and bladders" for the assembly and pre-stress is still not too late to be considered as a backup/future option.

Recommendation:

- Organize an internal review in the collaboration, to better integrate the best features of the previous FNAL and CERN developments to the further 11 T dipole development.

Charge 4:

Is the plan for models and prototypes well thought? Is the preliminary construction plan credible?

Findings and Comments:

- No, the plan as presented is not yet credible. In particular the technical linkages / decisions have not been presented in detail, a description of the features to be explored I the various models is absent, and how the model program informs the prototype and construction programs was not discussed.
- As presented in the plan results from both models and prototypes appear too late to inform the construction program.
- The construction plan is challenging with ~7 coils/year (20 coils total), including the assumption of no failures during the coil/magnet fabrication.

Recommendations:

- Modify the plan to emphasize the development process of the model magnets, practice coil windings, and practice magnet assemblies as much as possible.
- Increase the number of coils wound early in the program, such that any failures are accommodated with minimal overall delays and a ‘reserve’ of coils is available later in the production.
- Optimize the production rate by increasing tooling and concentrating construction in later years before LS2, creating time for feedback from model and prototype tests in the plan, and creating the possibility of reserve in the schedule.
- Define the requirements and goals for upcoming magnets on a case-by-case basis. This includes defining the actual electrical requirements, consistent with installation in the LHC.

Charge 5:

Are the design and manufacturing plans sufficiently well developed to engage in the upcoming significant procurements, i.e. Nb_3Sn strand and cable procurement and production, and magnet components procurement (collars, yoke, shells, etc.)?

Comments and Recommendations:

- Yes, RRP strand/conductor is sufficiently well established to be ready for LS2. There is no time for changes (key-stone, cross-section).
- PIT strand/conductor has not yet achieved the design specifications and thus not been demonstrated to be production ready.
- Mechanical structure (except end-part and wedges) still need to be demonstrated for the CERN model, so major procurements of these components might have to be delayed.

Recommendations;

- Integrate and establish the milestones for procurements into the overall project plan.
- Use PIT strand in production magnets after LS2.

Charge 6:

Is there any specific area in which the project is running important technical or managerial risks?

Finding and Comments:

- The mechanical structure & operational margin remain to be proven.
- The overall Management and Project structure was not adequately presented.
- Team integration (across sections, groups, Division and Departments) is required for the success of the project.
- The committee believes more proactive technical integration is needed across the whole 11T+Collimator Project and within the 11 T Magnet Project.
- The project schedule as presented is designed for meeting a target date, but does not seem to take into account the severe technical risks involved in each stage of the project.
- The committee did not receive a detailed project plan for the 11 T magnet fabrication portion of the project or for the overall project implementation for LS2. A complete project pan should be immediately developed and include the time required for placing procurement contracts.
- A risk plan should be developed which includes risk mitigation or elimination strategies.
- It is clear that the CERN magnet group in cooperation with Fermilab has a great deal of technical and fabrication experience as well as excellent production facilities, so the committee is confident that, provided the expertise is deployed correctly, this project can be successfully completed. The main question is on what schedule.

General Comments

This review has focused on the first phase of the 11 T dipole to be installed during LS2. Further project plans shall be re-visited and be separately reviewed, based on the progress in the first phase construction before LS2.

The PIT conductor should be further developed to be ready for the second phase, and there will be some room for further improvement. For example, as proposed by the conductor section/group and endorsed at the conductor review, the SC cable key-stone angle could be reduced in order to facilitate the use of PIT strands, in the following 11 T dipole project after LS2. This change would also lead to an improvement in the conductor performance of RRP cable, due to a reduction of local degradation during cabling, in the future.

The quench protection could be improved by using the CLIQ method in combination with the outer layer heater. Development and validation of an inner layer heater is risky and might delay the production schedule.

Reference;

2nd International Review of the HL-LHC 11 T Dipole for DS Collimation.
https://indico.cern.ch/event/354499/page/1

Appendix 1:

- Reports given on 8 December.

#	Subject	Preseted by
1	Welcome and introduction	*Lucio ROSSI*
2	The collimation project	*Stefano REDAELLI*
3	Overview of the 11T dipole project	*Frederic SAVARY*
4	Beam specifications	*Massimo GIOVANNOZZI*
5	Electromagnetic design	*Susana IZQUIERDO BERMUDEZ*
6	Mechanical design	*Friedrich LACKNER*
7	Quench protection	*Susana IZQUIERDO BERMUDEZ*
8	11T cable development and procurement strategy at CERN	*Bernardo BORDINI*
9	Design of the cryo-assembly	*Delio DUARTE RAMOS*
10	Design of the 6 m cold mass assembly	*Herve PRIN*
11	11T dipole electrical circuit	*Ludovic GRAND-CLEMENT*
12	Powering	*Hugues THIESEN*
13	ELQA and protection in the machine	*Arjan VERWEIJ*

- Report given on 9 December.

#	Subject	Preseted by
1	Models production data – CERN: Part 1 – Coil Technology	*David SMEKENS*
2	Analysis of the production data from CERN: Part 2	*Christian Hannes LOFFLER*
3	11T dipole design and fabrication at	*Alfred NOBREGA*
4	Visit of the large magnet laboratory in B180	
5	Visit of the magnet facility in B927	
6	Cold powering tests of the 11 T dipole model at CERN	*Gerard WILLERING*
7	Magnetic measurements and analysis at CERN	*Lucio FISCARELLI*
8	Summary of test results at FNAL	*Alexander ZLOBIN*
9	11 T superconductor thermal analysis	*Hugo Bajas*
10	Status of the tooling: Part-1, from winding to impregnation	*Raul MORON-BALLESTER*
11	Status of the tooling: Part -2, from collaring to cold mass finishing	*Christian Hannes LOFFLER*
12	Project plan & production strategy	*Frederic SAVARY*