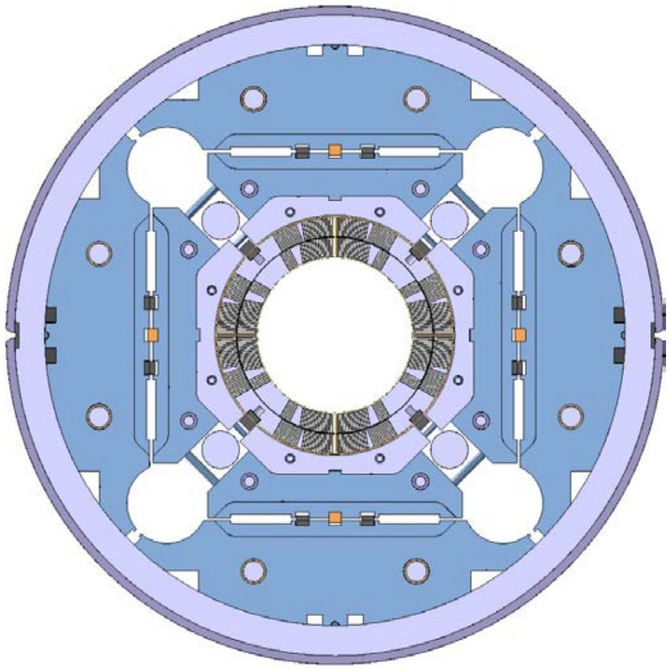
Report of HL-LHC/LARP International Review of Inner Triplet Quadruples (MQXF) Design

Review held at CERN, 10-12th December, 2014

The International Review Committee:

Joe Minervini (MIT, Co-Chair), Jim Kerby (ANL), Shlomo Caspi (LBNL), Alexander Zlobin (Fermilab), and Akira Yamamoto (KEK-CERN, Chair)

FINAL: 2015-02-04



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Executive Summary

The HL-LHC/LARP international review of Inner Triplet Quadrupole (MQXF) Design was held at CERN on 10-12th December, 2014.

The committee received 18 reports on the recent technical progress in the MQXF design and R&D efforts integrated in cooperation between the US-LARP and CERN. The reports also described the future project plan to meet the requirement for the MQXF magnets to be developed and ready for operation in the HL-LHC project, after the LS3 in 2023-2024. The committee summarizes its findings and advice as follows:

- The committee congratulates the team on the progress achieved in the MQXF design. We recognize the excellent teamwork, between CERN and US-LARP, and the significant roles and contributions made by young scientists and engineers to ensure the future project success.

- The MQXF program, together with the 11T dipole program, is a critical proof of Nb_3Sn magnet technology for high-energy accelerators. The reliable and stable operation of the MQXF magnets has to be the primary design and construction issue, because these magnets are to be operated in a demanding high radiation environment with very limited accessibility after the installation into the LHC-IR regions. For this reason, reliability and stable operation must be properly addressed during design and construction.

- The committee supports the general magnet design and, particularly, selection of a MQXF aperture of 150mm. It provides the space necessary for a sufficiently thick beam absorber screen to suppress radiation heat loads and damages due to the radiation dose accumulated in the magnet.

- Given the current understanding of the design and technology and the risks associated with the implementation of this design in the LHC Inner Triplets, the committee still finds possible improvement, and advises to:

- Increase MQXF operation margin by setting the magnet nominal operation current to be 75%, lowering from 80%, of the magnet short sample limit (SSL) along the load-line (LL). This can be realized by extending the magnet length and by lowering the peak field. The space for the extension should be available because of a major space saving realized by using the superconducting magnet, D1, located after the Inner Triplet.

- Test (train) all the production magnets up to 110% of the nominal operating current at the pre-installation test on the surface, as already considered in the design, in order to ensure the quench and mechanical margins and redundancy for long term operation. Thermal cycling tests should also be performed during the surface test to insure the magnets have good training memory after the thermal cycling.

- Keep a backup option for the Q2A/B magnet length, currently 6.8m, to be a half that length, because of insufficient experience with Nb_3Sn accelerator magnets longer than 4 meters. This may be important also from the viewpoint of the design for magnet quench safety considering the small Cu stabilizer ratio (Cu/no-Cu ratio of 1.2).

- Prepare for an alternate design with the Nb_3Sn cable, using a lower keystone angle, as suggested in the SC cable review, particularly for use with strand made via the PIT process, to ensure superconducting cable availability from multiple vendors, and to be available for the production magnets.

- Plan for expanding/strengthening the production and test facilities at HL-LHC/LARP laboratories involved in this program. It is critically important and imperative that they will be completed and available on time.

1. Introduction and Charges to the Review Committee

The High Luminosity LHC (HL-LHC) project was approved as first priority by the special CERN Council held in Brussels on 30th May 2013. In May 2014, HL-LHC was rated among the next decade top priorities of the US HEP program by the P5 committee, and in June 2014 the CERN Council approved its financing for the years 2015-2025.

HL-LHC is entering the final stage of design and prototyping: all technologies for the hardware upgrade must be fully proven by end 2016.

The replacement of the present inner triplet (IT) quadrupole magnets by new quadrupoles (MQXF), featuring much larger aperture and higher peak field, is the cornerstone of the upgrade plan. Tests of the short models of final design, foreseen in 2015 and 2016, and of the long prototypes, planned for end 2016, are on the critical path.

LARP has successfully built a series of quadrupoles of enhanced size and peak field; now LARP and CERN are engaged in a common program to build the first 1 m long demonstrator magnets, to be tested in 2015; testing of the first long prototypes is foreseen to start in 2016.

While the assessment of the final design is foreseen in 2016-17, at this stage it should be important to thoroughly review the magnet design and main manufacturing steps, because the CERN-USA collaboration needs to launch procurement of large size tooling and freeze key parameters for the prototyping phase.

The HL-LHC Project Leader and the LARP Director called an International Review and this review provides the first independent assessment of the MQXF design.

2. Charges given to the External Review Committee

The charges given to the External Review Committee is summarized as follows:

1. *Are the Functional and Technical Specifications for the 3 MQXF magnets (Q1, Q2 and Q3) properly developed and reasonably finalized? Do the 10-year long LARP experience on cables and magnets and the more recent experience in Europe support the chosen specifications?*
2. *Does the basic design of the MQXF in terms of the magnetic and mechanical structure, quench protection and thermal operative conditions meet the Specifications with sufficient margin? Based on the LARP and European experiences, what is the likelihood of meeting the Specifications?*
3. *Is the engineering design (including the 3D modeling and the interfacing with other systems) sufficiently developed to assess that there are no show-stoppers in the construction of magnet parts, cold mass assemblies and cryostat, including installation and integration in the machine? Is the magnet and circuit protection adequate?*
4. *Is the plan for models and prototypes well thought? Is the preliminary construction plan credible?*
5. *Is the envisaged work share, between CERN and US-LARP the best to maximize the chances of success while minimizing the cost and interfaces?*
6. *Is there any area or particular field where important technical or managerial risks are under evaluated or ignored?*

3. Findings/Comments and Recommendations for individual charge from the Committee

Charge 1:

Are the Functional and Technical Specifications for the 3 MQXF magnets (Q1, Q2 and Q3) properly developed and reasonably finalized?

Do the 10-year long LARP experience on cables and magnets and the more recent experience in Europe support the chosen specifications?

Findings and Comments:

- Not yet. However, the design is converging, based on the excellent long-term cooperative effort between US-LARP and CERN.
  - Some optimization of IR optics and magnet parameters is needed to reduce the risk of magnet production and LHC operation. Magnet acceptance parameters need to be formulated and included in the specifications.

- The interfaces across work packages need to be well defined and integrated into the specifications.

- The 10-years long US-LARP R&D experience has been well employed.

Recommendations:

-
- With respect to component manufacturing tolerances, the committee recommends to take into account the tolerances achieved during the fabrication of the US-LARP HQ magnet which could allow for some relaxation of the tolerances and potential cost savings.

- Test (train) all the production magnets up to 110% of the nominal operating current at the pre-installation test on the surface, as already considered in the design, in order to ensure the quench and mechanical margins and redundancy for long term operation. Thermal cycling tests should also be performed during the surface test to insure the magnets have good training memory after the thermal cycling.

- Keep a backup option for the Q2A/B magnet length, currently 6.8m, to be a half that length, because as yet there is no experience with a Nb_3Sn accelerator magnet of length greater than 5 m. This may be important also from the viewpoint of the design with regard to quenching, due to the choice of a small Cu stabilizer ratio (Cu/no-Cu ratio of 1.2).

- Prepare for an alternate design with the Nb_3Sn cable, using a smaller keystone angle, as it was proposed by the SCD team/section and encouraged in the previous superconductor and cable review, particularly when using strand prepared via the PIT process, to ensure availability of superconductor from multiple vendors. In the production stage, it would be preferable to have the same coil design, using cable with a small keystone angle, for both the RRP and PIT strands.

<u>Charge 2:</u>

Does the basic design of the MQXF in terms of the magnetic and mechanical structure, quench protection, and thermal operative conditions meet the Specifications with sufficient margin?

Based on the LARP and European experiences, what is the likelihood of meeting the Specifications?

Findings and Comments:

- No, the specifications have not been yet finalized with sufficient operational margin for such critical magnets under high radiation dose and very limited access for maintenance.

  - PIT cable has not yet met the I_c requirements.
  - The coil cross-section is being corrected for use of PIT cable.

- The cable expansion during reaction needs to be further understood and implemented in coil cross-section design.
- The coil preload level needs to be coordinated with the ultimate design gradient.
- The quench protection analysis should include the voltage distribution during quench in the nominal and heater failure scenario, and the cryostat quench protection analysis.
- The inner-layer and inter-layer heater concepts needs to be critically evaluated including their impact on magnet production and operation risks.
- The thermal analysis needs to include sensitivity to heat load variation due to uncertainty with beam absorber design and parameters.
- The coil insulation need to be sufficiently radiation hard against to the radiation dose to be integrated. It should be carefully confirmed in comparison with the coil insulation using "glass+mica tape" planned in the 11 Tesla magnet program in the same HL-LHC program.

Recommendations:

- Further optimization should be given in the short model program to demonstrate appropriate margin, including addressing the issues listed above.

Charge 3:

Is the engineering design (including the 3D modeling and the interfacing with other systems) sufficiently developed to assess that there are no show-stoppers in the construction of magnet parts, cold mass assemblies and cryostat, including installation and integration in the machine?

Is the magnet and circuit protection adequate?

Findings and Comments:

- The design is reasonably well developed for this stage of the project, and there is considerable experience to draw on to develop it further.

- The committee has limited the scope of the review largely to the magnet work packages. Interfaces to other work packages need to be further developed.

- Development of alignment specifications and the overall scheme was not covered in detail at this review.

- Magnet quench protection has a sufficient level of redundancy level taking into account traditional protection heaters and CLIQ.

Recommendation:

- Overall safety issues with respect to design and inspection should be confirmed as soon as possible. (see also the recommendation for Charge 1.)

- Development of alignment specifications and the overall scheme should start soon.

- The procedure of the magnet replacement under high radiation environment should be well established in the design stage, and it should include fixtures, tools, and remote handling, transportation, and the time scale which impacts on the machine availability, resulting in an effect on integrated luminosity.

Charge 4:

Is the plan for models and prototypes well thought?

Is the preliminary construction plan credible?

Findings and Comments:

- Yes, but some aspects need improvement. The number of planned models and tests is minimal: two at the US-LARP (based on the additional HQ experience) and three at CERN, to demonstrate reproducibility of the magnet performance, particularly for the field quality, even with different fabrication tools and fixtures. In a previous experience, both MQXA and MQXB programs started with three model magnets to confirm reproducibility, and resulted in five or more model magnets, including a reason of minor field design change required in the course of the model work process.

- The two full-scale prototype program, at least, is necessary to ensure the performance reproducible.

- The availability of the PIT conductor satisfying the specification may require more time to be ready for magnet production.

- The current schedule is tight, even though less tighter than the 11 T dipole program, in order to meet the plan to install the MQXF during the LS3 currently planned in 2023 - 2024. No failures are assumed in the current model work, and reasonable redundancy needs to be considered. For example, additional coil winding with a level of 15 %, already considered, should be well taken into account in the nominal schedule.

Recommendations:

- Each MQXF model work, whether by US-LARP or CERN, should have a clear list of design and performance goals, in addition to the clear objectives of each model and prototype program, in order to determine a credible level of the performance of production magnets.

- Contingency plans need to be developed to hold the schedule, and to be included in the general project plan.

Charge 5:

Is the envisaged work share, between CERN and US-LARP the best to maximize the chances of success while minimizing the cost and interfaces?

Finding and Comments:

- The work sharing and cooperation between CERN and US-LARP are exemplary. The committee congratulates the extremely successful international cooperation demonstrating the excellent progress reaching the common design and the magnet fabrication technology.

- CERN and US-LARP have many excellent resources and they seem well integrated and, enthusiastic, and should be able to carry out this upgrade project. The cooperative work and the close communication are enhanced by current IT technology that maximizes work efficiency.

- Design credibility may be enhanced by using common tools: especially in magnetic and structural design and analysis, thermal modeling, powering, and quench protection (se also the recommendation for Charge 1).

- The committee is very pleased to see many young scientist/engineers involved in this project with an extremely good atmosphere, but also advise that experienced members of the group should be assigned to ensure their training and supervision.

Charge 6:

Is there any area or particular field where important technical or managerial risks are under evaluated or ignored?

Finding and Comments:

- Evaluation of the overall failure mode scenario is missing.

- Technical risks can be minimized by focusing on the following issues:
  - Magnet operation margin in design and ultimate acceptance plan.
  - Beam screen design and integration with quadrupoles.
  - Necessity of coil cross-section change, in the US-LARP quadrupoles, based on RRP cable with optimizing and settling the strand design and the key-stone angle.
  - Use of PIT conductor in CERN quadrupoles (to keep multiple vendors).
  - If inner-layer protection heaters are to be used, their effect on coil cooling should be evaluated.
  - Utilize CLIQ for a redundant quench protection scheme.
  - General safety requirements: quenches, radiation dose, etc.
  - Management risks can be minimized by focusing on improvement of the design decision process and clear definition of responsibilities within the project and among related projects.

Recommendations:

- More work should be done on establishing a reliable quench protection system. The CLIQ scheme should be implemented in addition to the regular protection system using heaters, in order to provide redundancy (see also the recommendation for Charge 1).

- The time-period and work-flow sequence in case of a failure and necessary repair work should be well established. It is especially important to take into account that MQXF replacement work is not easy under the high-radiation and confined environment in the tunnel.

- The loss of integrated luminosity in such incident should be well evaluated and justified with the information shared among the relevant groups and persons.

General Comments

- The committee congratulates the progress achieved in the MQXF design. We recognize an excellent teamwork between CERN and US-LARP, and significant contributions by young scientists and engineers to ensure future project success.

Reference;
https://indico.cern.ch/event/355818/timetable/#20141210

Appendix 1:
The reports given during the review:
https://indico.cern.ch/event/355818/timetable/#20141210
- Reports given on 10 December.

#	Subject	Preseted by
1	Welcome and review charge	*Lucio ROSSI et al.*
2	MQXF Requirements and conceptual design	*Ezio TODESCO*
3	Feedback from conductor review	*Ezio TODESCO*
4	LARP and other programs' experience	*GianLuca SABBI*
5	MQXF support structure as extension of LARP experience	*Helene FELICE*
6	MQXF overall design	*Paolo FERRACIN*

- Report given on 11 December.

#	Subject	Preseted by
1	Magnetic design and analysis	*Susana IZQUIERDO BERMUDEZ*
2	Coil design and fabrication	*Miao YU*
3	Mechanical design and analysis	*Mariusz JUCHNO*
4	Quench protection and radiation damage	*Giorgio AMBROSIO*
5	Cooling and thermal analysis	*Rob VAN WEELDEREN*
7	CERN Q2 assembly procedure	*Juan Carlos PEREZ*
8	LARP prototypes assembly toward Q1-Q3 magnets	*Daniel CHENG*
9	Cold mass, cryostat and integration in the LHC	*Herve PRIN*
10	Feedback on MQXFS structure fabrication	*Pierre MOYRET*
11	Readiness of test stations for design validation	*Marta BAJKO et al.*
12	Short model and prototype plans	*Giorgio AMBROSIO et al.*