Test Facility Dipole: Conceptual Design Review Report

Review held on : June 11th 2020

Close-out held on : June 26th 2020

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The committee would like to thank the LBNL team for the quality and clarity of the presentations, and to compliment them for the quality of the work performed. Overall, the committee believes that the TFD conceptual design is well-advanced and set a solid stage to move forward with the project. Nonetheless the challenge is great, and we present below comments and recommendations, which should help the team facing it.

1. Are the magnet requirements properly defined and documented? Have interfaces with the final facility been properly documented?

The committee believes that more work is needed. The draft of the HTS Cable Test Facility Specifications has been useful to start the project. Nonetheless, its draft status and the presence of requirements believed to be outdated expose the project to significant risks.
Magnet and test facility are being developed by teams from different national laboratories. Work at the test facility has started and cryostat final design review is expected shortly. Therefore, interfaces must be defined as soon as possible.

Findings:

- A draft Test Facility requirements document is available based on users input. It contains specifications for the magnet field. The team believes that the specification for AC ripple field (Specification 2.3) does not apply to the magnet.
- Key spec: The design target is 16 T with 15% LL margin. The nominal (operating) target is 15 T (~20% LL margin). Aperture must be compatible with rectangular and circular sample holders.
- A mechanical interface document has been started. Some key parameters are already listed. At this time it is a living document.
- No electrical interface document was presented.
- During the review a concept for the mechanical connection between magnet and top plate was presented, and several team members acknowledged it may not be appropriate.
- During the review the possible use of CLIQ was discussed, but it appears that test facility team was not aware of this possible interface.
- Final design review of the cryostat is planned not later than October 2020

Comments:

- It is critical for a project of this size and visibility to have clear and approved functional requirements. Therefore, the LBNL team should prepare Functional Requirements Specification for the TFD magnet and have this document approved by all stakeholders. Since

functional requirements are driving both design and interface, this document is urgently needed.
- All interfaces with the cryostat must be finalized before the cryostat final design review.
- All interfaces with instrumentation/protection/cryogenic set up in the test facility need to be updated.
- Since magnet scope and test facility scope are pursued by teams at different laboratories, all interfaces between magnet and test facility must be identified shortly and should be finalized before mutually agreed deadlines.
- It may be useful to have an interface control document listing all interfaces (mechanical, electrical, protection, cryogenic, …), tracking their status and relevant documentation.
- Requirements and interfaces should be key elements for upcoming reviews.
- The complexity of operating a HTS insert in the TFD should also be considered at an early stage of the magnet + test station design. Possible interfaces (for instance mechanical interface with sample holder) and/or interactions (for instance from AC generator in test sample) between HTS test coils and magnet should be understood and addressed in this phase of the design.

Recommendations

a) **Clarify the project organization to deal with interfaces. Appointing a "system" scientist/Engineer would help.**
b) **Develop Functional Requirement Specification for the TFD magnet and have it approved shortly.**
c) **Identify all interfaces with test facility, and agree on deadlines for their finalization**
d) **Identify all possible interfaces and interactions between TFD magnet and sample holder, and agree with stakeholder on how to address them.**

2. Are conductor options appropriately considered? Are the plans for conductor selection and cable design finalization appropriate for this stage of the project, and have associated risks been identified?

Mainly yes.

Findings

- Two types of strands are considered to represent ends of a spectrum of strand available to the project: a modified strand based on the Hi-Lumi type (108/127, high Cu ratio 1.2, reduced tin, marginal Ic, well-established cost and production) and a CERN DEMO type one (162/169, lower Cu ratio 0.9, standard tin, higher Ic, more expensive).
- The cable is considered without core. First option has 44 strands with 1.1 mm diameter, alternative option has 48 strands with 1.0 mm diameter. The 44-strand option has more favorable cable aspect ratio.
- The cable options have some legacy from consideration of a graded design, which may no longer be relevant.
- Spool mass and spool tension are within the capabilities of the cabling machine at LBNL.
- In the coming months, test cables will be made with both options and characterization will be launched (winding test, extracted strand RRR, possibly stability current threshold Is)

Comments

- Given the fact that the Hi-Lumi wire has fewer sub-elements (108/127) and will be used as a large diameter strand, where e.g. 71 µm sub-element diameter will occur at 1.1 mm strand diameter, it will be important to perform stability analyses. This includes low-field instability with high heat release, which may push requirements for RRR into a range where Ic trade-back is not acceptable.
- The strain cliff could play a role, with target field being so high. Fortunately an aggressive heat treatment tends to mitigate the strain cliff.
- Wire design and heat treatment also have to target high H_irr to get sufficient load-line margin. The present Hi-Lumi strand and its standard reaction do not meet this requirement, although very aggressive reaction schedules can bring performance close to requirements. Verifying a conductor and heat treatment that meets requirements with appropriate confidence interval will require some R&D to gain statistics for heat treatments optimized toward high H_irr (ex: 680C/50h) and likely benefit higher tin 3.4:1 sub-element. Impact on RRR has some data but statistics are needed. Discussion with other actors who recently implemented high-tin strands with aggressive heat treatments, such as FNAL, could be useful.
- The choice of 1.1 mm diameter strand and 44 strand cable is driven by having the same aspect ratio of FRESCA II cable. This is a good point, nonetheless it may be useful to consider also other factors in the baseline selection, for instance: cable mechanical stability, cable behaviour in hard-bending region before and after heat treatment, instability threshold, and impact on quench protection. It may be beneficial to make cable samples with 48 1-mm strands in order to be able to compare pros and cons of both options.
- The coil cross-section has a strong advantage of being flexible and could accommodate further optimization such as a change of cable without major impact on the project.

Recommendation

a) Follow the plan presented for making cable samples with both strand options, and if possible expand it to cover also cable alternatives.
b) Perform thorough characterization of strand and cable options before review of wire specifications.
c) Seek information from other institutions about recent developments using aggressive reactions and high-tin subelements, including topics such as the strain cliff, stability threshold, and RRR trade-back.

3. Has the project team properly reviewed and considered design alternatives?

Yes.

Findings:

- Several designs have been presented, all relying on block design geometry. The team presented also designs and options studied by previous projects, such as Dipole-first IR for HL-LHC and EDIPO conceptual design study, which developed cos-theta designs but did not fabricate them.
- Grading has been considered initially but due to the associated complexity, this option has been disregarded.
- Quench protection is based on energy extraction, and the team demonstrated that with conservative assumptions 15-T operation is safe, whereas 16-T operation is at the limit of

maximum acceptable hot-spot temperature (350 K). Less conservative analysis is expected to demonstrate margin also at 16 T.
- The team is planning to study the option of adding CLIQ to the protection system.

Comments:

- The choice of the block design option is supported by the committee based on the successful performance of FRESCA II magnet and the requirement for rectangular aperture.
- Removing alternatives that use grading for this one-of-a-kind magnet is fully supported by the committee.
- The committee appreciates the low-risk criteria used by the team in the choice of alternatives. Minimizing risks is appropriate for the design of a magnet that will be the main component of a unique test facility.
- Alternative protection options could assure that the final design has adequate redundancy for a test facility.

Recommendation:

Complete the study of quench protection based on energy extraction and CLIQ in order to assure that final design has adequate redundancy.

4. Is the design team using appropriate design and analysis tools?

Yes

Findings:

- The analysis presented used the usual tools in the community
- The most up to date approaches are being considered: fragile material (fracture), Ic reduction to stress.

Comments:

- In terms of protection, the use of the user-defined elements in ANSYS is part of the next step. The committee supports strongly this approach.

Recommendation:

As soon as possible, rely on measured Ic data for the design.

5. Is the design at the proper level of maturity for this stage in the design? Is the project managing the design process to meet performance requirements while minimizing project risk?

Mainly yes

Findings

- Magnetic field design, mechanical design, preliminary protection studies and CAD modeling have been presented.

- Two magnetic field designs have been presented: a LD-style design with 2 double layer block coils per pole that are not aligned horizontally, and a Fresca2-style design with 2 double layer block coils per pole that are aligned on the outer edge.
- Mechanical design:
  - The designs are presented using the LD1 shell.
  - From a stress stand-point, LD-type design is favorable and it has been chosen as the baseline. Another advantage is the balanced UL between the 2 coils. In the Fresca2-type case, the upper coil UL is close to the limit of the cable UL fabrication capability.
- CAD design: the winding tooling is under discussion. The implementation of the tilting winding table (Fresca2) is considered.
- Fresca2 reached ~80% of short sample Ic. The limitation was in one coil, with quenches triggered by mechanical motions at the transition between straight section and flared ends. Since the limitation is only in one coil, it is not clear if it is due to an intrinsic feature of the flared ends or a coil fabrication issue.

Comments

Magnetic design:

- The fact that the operating margin is of only 20% could be a concern. The fact that Fresca2 was never pushed beyond that point to minimize risk keeps the question of the reasonable margin open. It is not clear that an increase of preload in Fresca2 would have allowed a higher plateau to be reached, given the suspected nature of the quench. Therefore, in the case of the TFD, increasing the margin on the loadline could be considered in order to lower the risk on the project.
- In addition, it would be useful to perform a sensitivity analysis in terms of coil width (number of turns) versus short sample field. Given the fact that this magnet is one of a kind, coil efficiency does not have to be the driver.

Mechanical design

- Strain gages are planned to be used to guide the preload of the coils. This approach is encouraged by the committee. However, experience and lessons learned with SG data versus model in past block-type magnet should be reviewed.
- In some past magnets, a good match between SG data and model was found during cool-down using a frictionless condition between yoke and shell. It would be interesting to probe the sensitivity of the model to this friction condition.
- Assembly tolerances between the 2 poles should be considered early in the design. The contact between the two poles is indeed a critical area in terms of correlation between SG data and modelling. It would be useful to study the impact of a few tenths of mm between the 2 poles on the coils preload and on the expected SG data.
- Flared ends appear to be a weak point in the block-type designs (Fresca2 and HD2-3 series). Unfortunately, there is no correlation between magnet behaviour and ANSYS modelling. However, it seems important to look closely at the improvement which could be made to support more efficiently this region. This may be the only weak point of the selected design. Therefore, it may be useful to intensify efforts (detailed analyses, engaging the broader community for instance through a workshop) to mitigate the risk of performance limitations in this region.

- The thick stainless-steel shim in between the two coils has to be carefully studied and engineered. In the transient regime, forces due to eddy currents may play a role. It is in a critical position for the coil.

Protection:

- The choice of not having protection heaters due to their lack of reliability (electrical failure) has been discussed. It would be useful to document this choice.
- A quench protection system with sufficient redundancy for a test facility, taking into account possible interaction with test samples, appears to be a necessity.
- The considered delay to protection trigger (5+10+2 ms) is quite ambitious in particular in the case of operation with a HTS insert inside the magnet. In this case the protection would need to be decoupled.

CAD+ tooling:

- CAD modelling has the proper level of maturity at this stage.
- Sufficient clearance for coil assembly should be looked at early in the process.
- The question on ensuring pole gaps during heat treatment to allow for dimensional changes has been discussed. It seems that discussion is still ongoing in the LBNL team. The committee would like to point out that there are difficulties in terms of implementation in the tooling. In addition, dealing with non-uniform coil length would require to have adjustable "boats" and shims. However, given the length of the coil, this fabrication step makes sense. There is no consensus in the community on this topic. The committee suggests making enough practice coils to optimize the process.

Recommendations

a) Magnetic design

i. **Perform a sensitivity analysis in terms of coil width (number of turns) versus short sample field, aiming at increasing margin on the load line**.

b) Mechanical design

i. **Build margin into the support structure in terms of ability to apply preload to the coils. Using a thicker shell should be considered.**

ii. **Ic reduction due to stress should be quantified and accounted for.**

iii. **Intensify design effort to reduce the risk of performance limitations caused by quenches located at the start of the flared ends.**

c) *Protection study*:

i. **Consider the use of a lower hot spot temperature target.**

ii. **Interact closely with the CERN team who will test the Eucard or Eucard2 in Fresca2 in the coming months.**

iii. **Complete development of a redundant and robust quench protection system adequate for a test facility and its use with different types of samples with different requirements.**

d) Coil design:

Electrical integrity is a key issue in Nb_3Sn coils. Plan for a robust electrical insulation scheme starting at this early stage.

6. Have critical technology issues and relevant decision points been identified? Is the team benefiting from all relevant experience from the broader community?

Mainly Yes

Findings

- Key decision points have been clearly explained:
  - Block type
  - Graded vs non graded option
  - LD vs Fresca 2 style
- Upcoming decision points have also been stated:
  - Cable run and cable/XS strand characterization
  - Winding table

- The TFD is based on studies and construction of block type magnets and large aperture magnets.
- Information exchange is ongoing with the different actors of the community.

Comment

- Some technical challenges related to the type of samples/insert to be tested in the bore should be looked at closely in particular in terms of protection.

Recommendations:

a) **Collect and build upon "lessons learned" about key topics as detailed in previous points.**
b) **Follow closely the test of the Feather/Eucard/Eucard2 inserts in Fresca2.**

7. Is the design team properly staffed? Are there areas where additional resources should be provided?

YES regarding the magnet design team
All the team members have a wide experience of magnet design and fabrication, in particular on Nb_3Sn magnets and on block-type concepts. Each field of the magnet design is covered by relevant magnet engineers and the project is managed by senior experts in the domain. At this stage, the committee does not see a need for additional resources

Regarding the project team, as mentioned in 1., a system engineer should be added to cover all the interface questions.

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