HTS Test Facility Dipole Magnet (TFD)
Preliminary Design Review Report

Review held on: Feb 16th 2023
Time: 7 am-11 am CA time, 10 am - 2 pm (US eastern time), and 4 pm - 8 pm (Paris time)

Review close-out: March 16th 2023
Time: 8am CA time

Reviewers:
Review Committee: Helene Felice (Chair), Giorgio Ambrosio, Lance Cooley, Etienne Rochepault, Juan Carlos Perez
Observers: Steve Gourlay, George Velev, Ken Marken, Guin Shaw

The committee would like to thank the project team for the high quality of the presentations and for addressing the question asked after the review meeting. This magnet is of primary importance for the US and for the world wide Nb_3Sn community pushing the technology to a new limit. Overall, the magnet design is on the right track. Nonetheless, given the challenge of the task, additional interaction with the worldwide community could be beneficial.
This report has been written in the spirit of supporting this important project through comments and recommendations aiming at making the project as strong as possible.

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

Partly yes.

Findings
In the conceptual design review report from June 2020, the need for a complete functional requirement specification has been strongly underlined. Such a document was not presented at the review.
It is understood from the discussion during this review that the communication with stakeholders seems to be complex. In particular, collecting the requirements from the users in a timely manner is difficult. Decision from the project team is to do the best that can be done in terms of technical choices, make the stakeholder aware and take into account disagreements if any. The communication with stakeholders is done mainly through workshops.
As an example, the 750 mm straight section set as the present design choice is coming from iteration between initial requirements from the FES community, infrastructure constraints (weight limitation) at FNAL, and risk mitigation on the magnet design (limitation of the hard-way bend design). This number was presented at the LTSW workshop and tacitly agreed on.
Regarding the interfaces, a mechanical interface document was provided to the committee describing mainly the interfaces between the assembled magnet and the FNAL High Field

Vertical Magnet Test Facility. The document mainly describes the magnet mechanical interfaces with the cryostat.
To the knowledge of the committee, there is no interface document on the electrical and instrumentation interfaces.

Comments
Despite the difficulty in converging on a set of requirements, the project would gain in clarifying the magnet requirements in terms of size and shape of the bore, and the type of samples or inserts to be tested.
Regarding protection, the detailed protection scheme of the magnet as part of the test facility was not presented during the review. It is understood that the magnet safety/protection system is being designed as part of the test facility protection system as presented in HFVMTF Cable Test Facility: First Workshop on User Interfaces (21-22 novembre 2022) · INDICO-FNAL (Indico). However, to the knowledge of the committee there are no ongoing studies about possible electromagnetic coupling between the inserts/samples and the magnet itself. This topic should be investigated along with any other coupling (mechanical thermal) which could occur between samples/insert and magnets.
It would be useful to get feedback from:

- the feather2 insert integration in Fresca 2
- the EUCARD/EUCARD2 integration studies in Fresca2
- the Feather2 insert test in Fresca2.

Recommendation

a) **identify critical parameters/requirements and collect them in a "Critical Requirement Specification" and have it approved shortly or at least acknowledged by stakeholders.**
b) **Identify and document all interfaces with test facility, and agree on deadlines for their finalization.**
c) **Identify, document and study all possible coupling between the magnet and the samples/inserts to minimize risk of problematic interaction.**

2) Are the plans for cable design finalization appropriate for this stage of the project? Have associated risks been identified? Does the plan provide adequate risk mitigation?

Yes

Findings
A dedicated wire review was held in October 2021: TFD Wire Specification Review (28 octobre 2021) · (Indico) (lbl.gov) and did not cover the cable fabrication.
This preliminary design review presented the 3 stage cable development program put in place by the project: short cable, prototype and production cable fabrication. The last stage has not started yet.
Development and prototype cables have been completed and final cables achieved goals. Developmental cables exposed risks and provoked effective corrective actions. 1303-3

demonstrates improvement of cable geometry and properties, as well as readiness for production.

Comments

The committee is concerned that these cables may be close to the manufacturing limits for strands of this type. Mapping strands to produce narrow statistical property spread could provide margins and reduce the impact of unknowns, although this might require purchase of extra strand spools.

Digital image analysis of cable facets is a new capability for cabling technology. Evidence was provided that this new information source can warn of problems before an incident occurs. This will reduce risk and is a strong asset to the project.

The committee strongly supports the fabrication of the Cu cable UL but is concerned about the limited number of SC UL planned for the project. It is understood that some contingency is available to the project but which is not targeted yet. The committee encourages to consider procuring more strands in view of more cable UL.

Recommendation

a) **Select strand maps within statistical property ranges more narrow than given by strand specifications and control limits to reduce cable manufacturing risk and increase margin to mitigate downstream unknowns. Consider purchase of a few additional strand spools to accommodate maps.**
b) **Consider procuring more strands for additional coils.**

3) Is the design team using appropriate design and analysis tools?

Yes. The team is using all the state-of-the-art design and analysis tools available today in the community.

Findings

The analysis presented used the usual tools in the community. The mechanical analysis is at the forefront of the work done in the accelerator magnet community. The committee congratulates the team for this work.

The final magnetic design was not fully presented.

It is understood that all the design was done at 16 T but the results at 15 T which is the operating condition were not shown.

By design, the load line margin is 20 % at 15 T and 1.9 K. This margin remains at 20 % using the lower specified wire Ic from the wire spec and 5% cabling degradation. Based on strand Ic measurements of wires from the cable development program, the margin goes up to 23 %, including 5% cabling degradation.

Reversible and irreversible strain effects on Ic have been studied. In the high field region, due to unloading during operation, there is no reduction of the critical current. However there is a concern about irreversible degradation induced during assembly and cool-down. The considered mitigation actions are a higher heat treatment temperature (680°C) and reducing the assembly preload target.

Comments

Magnetic analysis

The question of the reasonable margin remains open in the community.

The committee acknowledges the large effort made by the team on the computation of the margin using Ic data and strain impact. The possibility to rely on strand characterization done by Najib Cheggour is a real plus for the magnet design.

All possible mitigation actions to keep the load line margin of at least 20% should be considered.

Mechanical analysis

The coil design criteria considered appears to be high (175 MPa at RT).

In general, the results presented to the committee are based on nominal conditions. A lesson learned from all the past experiences is to include as early as possible in the mechanical analysis the uncertainties related to manufacturing.

- Exploration of the impact of deviation from nominal (tolerances, misalignment…) should be performed. The mechanical interfaces where some gaps could occur should be looked at (such as between inter-coil spacer and poles for instance).-
- A sensitivity study of the material properties used in the mechanical model should be considered to prepare for the real assembly.

The implementation of a “soft bullet” seems challenging in practice. Going from FEA to manufacturing may require some mock-ups (consider if possible using existing block coils/structure for a mechanical model).

It is not clear if there will be a mechanical interaction between the magnet and the sample holder. If there will, this should be investigated.

Quench protection

Some results were presented showing a hot spot temperature under control (<180 K) with a dump resistor of 130 mOhm leading to a voltage of 2 kV across the magnet terminals. Symmetric grounding is of course helping but this voltage level could be a concern as we need to consider the test level to validate the dielectric integrity at room temperature (at least 2xU+500 V). Particular attention should be paid to the electrical insulation in the magnet.

Recommendation

a) **Introduce studies to account for parts tolerances and coil imperfection despite the smart shims.**
b) **Perform parametric studies to account for coil material properties uncertainties.**
c) **Consider mock-ups to validate key design choices.**

4) 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?

Mostly yes. This review concerns a design which is at the preliminary design stage.

Findings
The design parameters are collected in the TFD Coil and Structure Parameter Document.
As mentioned in 1) , a document summarizing the critical requirements is still missing.
On the conductor side, the project appears to be appropriately aware of the strain irreversibility cliff. Project is also aware of the risk for local strain enhancement, e.g. due to popped strands at the hard-way bends.
On the coil fabrication side, several aspects such as the layer jump and hardway bend have been probed by mock ups and tests.
On the assembly side, the baseline approach has been developed consistently with the LBNL team's large experience on the topic.
No documentation was presented showing structural and electrical design criteria. Criteria for conductor strain and for mechanical analysis were mentioned during the review.

Comments
The shell based structure is undoubtedly very well mastered by the members of the project team. However, the assembly of the block dipoles remains delicate.
At this stage of the design, it would be interesting to propose a pre-stress strategy and the range of pre-stress considered accounting for non-nominal conditions (in terms of contact conditions, parts tolerances for instance).
As mentioned in 3), it is a real asset to the project to benefit from strand measurements as a function of strain and to implement them in the mechanical analysis. However we lack experience on this type of analysis. It would be useful to validate this method by applying the same methodology to a few existing already tested magnets.
It may be useful to collect all design criteria (for superconductor, structural and electrical criteria) in a single document and have it reviewed.

Recommendation

a) **Validate the methodology used to account for strain dependence on existing magnets.**
b) **Document all design criteria and have them reviewed.**

5) Have critical design features and fabrication tooling been identified and solutions properly advanced, in particular for the coil? Is the team benefiting from all relevant experience from past projects and the broader community?

Mostly yes.

Findings

The detailed design has been carried out for the inner coil and associated tooling assuming that the outer coil will be similarly designed.

The coil design is strongly based on experience in HD2/3 and Fresca2 magnets. Lessons learned are being implemented in the TFD design. The team obviously benefits from a lot of experience from its members, from in-lab developments, and from the feedback from the community.

Comments

General comments related to coil fabrication

The coil fabrication is usually the critical path of Nb_3Sn magnet projects. Validating as much as possible the tooling and procedures with qualification tests before the first Nb_3Sn practice coil is highly encouraged.

The manufacturing of a first dummy Cu coil should be considered to debug the tooling and fabrication processes. The dummy Cu cable could be used for this purpose.

The plan to have a complete Nb_3Sn practice coil is also strongly supported by the committee. To learn as much as possible from this practice coil, it would be useful to establish in advance a plan about the expected inspection, measurements and tests to be performed on the practice coil once completed.

Coil Reaction Tooling

A particular attention must be paid to the segmented table behavior during heat treatment. According to FRESCA2 reaction tooling experience, this may not be straight-forward.

Unlike FRESCA2, different gap dimensions are foreseen between pole segments and heat treatment table segments. Sliding is assumed to be ensured by Mica.

To probe this concept, it is recommended to plan for tests and mock-ups before the Nb_3Sn practice coil.

Coil Impregnation Tooling

Having a “square box” around coil and fillers will facilitate the mold leak-tightness compared to FRESCA2 impregnation mold.

Having a filler piece in 2 parts to cope with coils of different dimensions after reaction seems a good solution.

There is a concern regarding the resin flow inside the mold. It is possible that the resin will follow preferential paths leading to dry areas at the end of the impregnation process (similar experience on some FRESCA2 coils). For this reason, an impregnation test using a copper coil will be useful to validate the process.

Electrical insulation

The committee agrees that AL_2O_3 plasma-sprayed coating of the poles is a good alternative to improve the electrical insulation. Coil to spacer insulation scheme should also be defined carefully.

The metallic inter–coil spacer is a new feature of the TFD magnet. A proper electric insulation of this component is critical in particular during quench and should be studied in detail.

In general, the electrical ground plane insulation in 2D and 3D should be defined at an early stage.

Recommendation

a) **Develop mock ups and test beds to probe the behavior of the reaction fixture during heat treatment.**
b) **Electrical integrity is a key issue in Nb_3Sn coils. Plan for a robust 3D electrical insulation scheme as soon as possible.**
c) **Consider fabricating a Cu practice coil prior to the Nb_3Sn practice coil.**

6) Have design and fabrication risks been properly identified, and are they being tracked and mitigated at a reasonable level?

Mostly Yes.

Findings
A risk register along with risk analysis has been put in place and is tracking progress and mitigation actions.

Comment
The creation and feeding of the risk register is definitely a strong addition to the project with respect to the previous review.
As listed in the risk register (risk R-FI-01), the test configurations of the samples/inserts are not yet finalized. From the table of risks presented during the review, mitigation action is not really in place regarding that point. Holding workshops and discussion is definitely useful but some documentation should formalize the decisions. As detailed in 1), getting an interface document with critical parameters finalized could help.
The recommendation list from the previous sections will contribute to the risks mitigation.

Recommendation

a) **Coils are the heart of the magnet. Procuring more conductor will strongly mitigate the project technical risks.**
b) **This magnet is an important milestone for the US as well as for the world wide SC magnet community. More time should be allowed for the next technical magnet review.**