Fermilab

Final Report

Director's CD3 Review of HL-LHC AUP

July 28-30, 2020

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1.0 Executive Summary

Committee chair: Rich Stanek

The CD3 Director's Review for the HL-LHC Accelerator Upgrade Project (AUP) was held on July 28 to July 30, 2020. The review was conducted remotely with an agenda that included presentations by the project and adequate time for questions, answers, discussions and drill-downs. The AUP Project is responsible for the design, construction, and delivery to CERN of ten Q1/Q3 Inner Triplet Focusing Quadrupoles and ten Dressed SRF Crab Cavities as described in the AUP Project Execution Plan. CD1/3a was approved in Oct. 2017, allowing procurement of the Nb_3Sn strand and CD2/3b was approved in February 2019, allowing fabrication of all cables and coil parts, and construction of a fraction of coils, magnets parts and cavities. The Total Project Cost (TPC) is $242.7M, with a CD4 approval of mid 2028, allowing 33 month of schedule contingency. The current funding profile is adequate and projected not to limit progress under the baseline plan. However, future COVID restrictions or a resurgence of the virus will require an additional review of contingency usage and the need for TPC adjustment.

The AUP Project is well managed. The project has an experienced and talented management and technical team, which at this stage, benefits from successfully executing work associated with CD3a and CD3b. Project mechanics, including cost/schedule, ES&H and QA reporting, are in place and operating smoothly. The commitment to traceability of requirements, interface controls, configuration management and documented acceptance criteria is exemplary and a model for future projects.

The project integrates work from multiple partner labs (FNAL, BNL, LBNL, JLab, SLAC, and ODU), and the entire team seems to be functioning well. Frequent meetings of the project team help keep all parties in sync. Communication with CERN appears to be frequent and effective. It is important that this communication continue to assure that as the project proceeds any required changes to requirements or acceptance criteria are mutually agreed upon so that the final components are ready to be handed over for integration and installation.

The AUP Project has made very impressive progress since CD2/3b. The team has taken advantage of the early CD approvals to perform necessary R&D, complete designs, demonstrate performance and substantially advance the project. Nonetheless, it must be remembered that the technologies employed in AUP (Nb_3Sn accelerator quality quadrupoles and RFD crab cavities) are very challenging and push the state of the art. The understanding of the technologies, particularly Nb_3Sn magnets, is still evolving and there are lessons learned from each magnet built and tested. Therefore, in a production project such as AUP, it is critical to minimize risk, where possible, and make decisions that allow for adequate testing and verification.

The Director's Review Committee recommends proceeding to CD3 after recommendations have been addressed.

Once the AUP Project completes its deliverables, the project can wind down. However, the Committee believes that subject matter experts working on AUP should stay engaged (to work with CERN) until the components are operating in the LHC. This may require a funding source outside the current AUP Project.

2.0 Project Management

Subcommittee: Mark Palmer*, Steve Nahn

Charge Questions:

- Are the need, technical justification, and schedule justification clearly articulated and sufficient to support the activities identified for the CD3 scope?

  Yes.

- Have all risks for the CD3 scope been identified, and are cost and schedule contingency adequate and commensurate with the risks relevant for the execution of the CD3 scope?

  Yes. Under normal circumstances, the Project risks completely cover the baseline scope. With COVID-19, the heightened level of uncertainty implies special attention will need to be continually applied.

- Does the project understand its dependencies on outside resources such as international collaborators?

  Yes. The remaining CERN deliverables are due imminently, and the project is working around COVID restrictions to maintain the schedule.

- Is the project appropriately responding to and planning for impacts from COVID19?

  Yes. The project should continue to evaluate potential impacts specifically on fabrication and assembly steps being carried out for the first time, where new surprises are more likely.

- Is the required documentation complete at a level necessary for CD3 and have recommendations from previous reviews been appropriately addressed?

  Yes. There are minor details that should be implemented before the CD3 IPR.

- Is the project being well managed, and is the project team being properly supported by the participating laboratories and Fermilab, in particular?

  Yes. Absolutely. Throughout the technical and managerial staff and across each of the participating institutions, it is evident that the performance and cooperation is excellent.

- Is the project ready for approval of CD3?

  Yes, pending the resolution of the pertinent recommendations from this review.

Findings

- The HL-LHC Accelerator Upgrade Project (HL-LHC AUP) is the U.S. in-kind accelerator contribution to the HL-LHC Upgrade of the LHC, for which U.S. scientists can provide unique expertise. Its baseline scope consists of Interaction Region Focusing Magnets and Crab Cavities. The total project cost is $242.7M, with an CD4 approval of mid 2028, allowing 33 months of schedule contingency.

- The Project has been baselined since February 2019, and has had two iterations of CD-3 approval of selected scope, the first for Nb_3Sn strand in October 2017 and the second for Fabrication of Magnet Coils and parts and Fabrication of pre-series magnets in Feb 2019. Thus the team is very well seasoned and experienced with the requirements of a DOE project.

- As of the May reporting period, the Project was 35.8% complete, with an EAC of $195.1M, increased by $3.9M since baseline - through baseline changes and a bottom-up estimate to complete analysis. The EAC contingency on Work-to-Go is 37.6%. The project has fairly steady EVMS performance numbers, with CPI between 1.02 and 1.05 and SPI between 0.93 and 0.97 for the last 12 months. Current period BCRs have been executed monthly to move work affected by the COVID-19 Pandemic to keep the baseline predictive.

- The Project has accelerated development of the final design of the Crab Cavities such that it can be included in the scope for "ready for Fabrication" approval, thus promoting this review from CD3c to a full CD3 on all remaining project scope, which amounts to $74.6M BAC. As many of the procurements have been covered by previous CD3 approvals, this cost is dominated by labor to fabricate the final deliverables.

- The deliverables of the Project are integrated into the International HL LHC Upgrade, managed by Host lab CERN. There is a complete set of Functional Requirements, Material Approvals, and Acceptance Criteria, most of which is already finalized and agreed upon by both entities, with the remainder expected to be complete by the time of CD3 IPR.

- The Project team presented an exhaustive set of control protocols for design changes, interface management, Quality Assurance, Risk Management, Configuration Management, and document control. Recent efforts have been made in development of Transportation of deliverables plans and handling of Non-Conformant components.

Comments

- This Project is very well staffed with a professional, experienced team that should be congratulated for thorough and excellent presentations and productive, open discussion during this review.

- Projections of COVID impacts utilize 3 standardized scenarios that the Project has described very well in terms of efficiency impacts and a preliminary risk analysis. Given that key portions of the

upcoming work involve production tasks (e.g. horizontal cryostating) that will be carried out for the first time, the impact of COVID limitations on manpower and oversight could impact the project's ability to effectively evaluate and incorporate lessons learned on its way to full production. Addressing such risks in greater detail may be warranted before CD3.

- Integration of the project team across the participating laboratories is strong and we commend the project management group on the robustness of their approach and their commitment to the level of integration incorporated into their approach.

- Some relatively recent changes at DOE should be reflected in project documentation, eg PEP, Monthly reports, etc. For example, Project Executive Binkley -> Kung, Head of OPA Lutha -> Fisher. In addition, anticipating the recommendation to proceed to CD3 OPA review the tailoring strategy of the PEP should be adjusted accordingly.

- The Project has a solid framework for the acceptance of deliverables by CERN, based on testing of the individual components. However, several review committees have expressed concern that the components may not be integrated and fully tested in their final configuration until well after any modifications are possible.

- The Project focus on planning transport issues for hardware delivery is timely and provides a strong basis for managing these issues through project completion.

- The technical groups have noted 2 areas, in particular, where the acceptance criteria for delivery of components should be carefully reviewed with the CERN HL-LHC Project Team. These are (1) the ultimate current testing criteria for the quadrupoles (including the relative limits used for vertical and horizontal testing) and (2) whether a more integrated approach to testing RF components before final delivery could be developed with CERN.

- We note that the MOU between Fermilab and CERN that covers deliverables has not yet been signed. Since technical agreement has been achieved, we believe that this should not impede the project's schedule to CD3 approval.

Recommendations

1. Before the start of cavity production, explore with CERN HL-LHC possible re-distribution of the one year of additional float from the LS3 shift to allow for further systems tests of the RF Dipole Crab Cavities, in particular the couplers, in order to reduce the risk CERN carries on the integrated performance.

2. Continue utilizing the present AUP current requirements (i.e. nominal current + 200 A) for pre-series magnet tests to ensure that the project can carry out pre-series cryostat assembly and magnet tests in a timely fashion.

3. In light of recommendation #8 below, discuss with CERN HL-LHC and DOE the mapping of the ultimate current acceptance criterion to an objective KPP requirement and the nominal current

acceptance criterion to a threshold KPP requirement for the project. This discussion should be completed prior to the CD3 ESAAB.

4. Extend the analysis of COVID risks with particular attention to new production line startup with constraints on manpower/oversight in preparation for the CD3 Review.

5. Obtain concurrence from the CERN HL-LHC Project to move forward with the pre-series test program using the presently planned AUP current requirements and then proceed to the CD3 IPR.

3.0 Cost & Schedule

Subcommittee: Jeff Deal*, Marianne Bossert, Laurie Casarole, Josh Byrd

Charge Questions:

- Is the baseline resource-loaded schedule adequate to serve as the performance baseline for the CD3 scope?

  Yes. The project has already been through CD2, -3a, -3b for well over a year. As a result the processes, reports and systems are well established and the project CAMs and support staff have strong knowledge of and comfort with the baseline resource-loaded schedule. The additional scope associated with CD3 (previously split into CD3c and CD3) appears to be well understood and incorporated into the resource-loaded schedule. Activities appear to be at a level that allows the project team to adequately plan, deliver, and measure performance. The necessary resources for project completion are detailed in the Basis of Estimates (BOEs) and incorporated into the schedule.

- Have all risks relevant for the CD3 scope been identified, and are the cost and schedule contingency adequate and commensurate with the risks relevant for the execution of the CD3 scope?

  Yes. All risks for the project, including the additional CD3 scope, appear to be identified in the risk register and analyzed through simulations to calculate adequate cost and schedule contingency to deliver the project at a 90% confidence level.

- Is the project appropriately responding to and planning for impacts from COVID19?

  Yes. Risks related to COVID-19 have currently been evaluated and analyzed outside of the risk register. The project is planning for potential impacts of three scenarios of COVID-19 related operational restrictions. Analysis has been done to quantify what the cost and schedule impacts would be under each of the three scenarios. Baseline Change Requests are being completed on a monthly basis to account for realized impacts to the project due to COVID-19 operation restrictions.

- Is the required documentation complete at a level necessary for CD3 and have recommendations from previous reviews been appropriately addressed?

  Yes. Documentation has been provided and appears to be complete for the CD3 review. Recommendations from the January 2020 IPR appear to be addressed (shipping detail and CERN milestones integration for instance) and the project did complete an April 2020 bottom up ETC exercise and incorporated the results into their baseline.

Findings

- The US HL-LHC Accelerator Upgrade Project Total Project cost (TPC) is $242.72 and the Performance Baseline is $191.2 with remaining cost contingency $51.5M (42% on work to go) and 33 month (36 month in Jan 2020 IPR review) of schedule contingency. May 2020 CPR: BAC $191,186,730 and EAC $195,096,654

- The schedule is resource loaded in Primavera (P6) and consists of 4,921 activities. The resource loaded schedule is then imported into Cobra for the application of burdens. The Deltek Acumen Fuse scoring indicates a schedule quality of 85.9% (baseline).

- The Risk Register identified a total of 95 risks which includes 83 threats and 12 opportunities. Update since IPR in Jan. 2020, 5 risks were retired, 2 new risks added and 14 had a status change. The Monte Carlo Analysis indicates for a 90% confidence level the cost uncertainty of $20M and 27.5 months for the schedule uncertainty.

- The project has a Change Control Process in place and has prepared 85 baseline change requests to date and is trending approximately 6/month.

- A bottom up ETC exercise was completed in April 2020. Control Account Managers (CAM) reviewed the 119 Basis of Estimates (BOEs) which resulted in 44 BOEs being revised, 8 new BOEs added, and 4 BCRs, one at each Level 2, which resulted in a $4.6M cost impact.

- Three CAMs (Magnets, Cryo-Assemblies, and Crab Cavities) were interviewed and were well versed and able to drill down into their BOEs, schedule, variance reports, etc. Each CAM demonstrated ownership of their risk register and how it contributed to the overall project.

- OPSS at FNAL formalized a COVID-19 Scenario Analysis June 2020. This analysis uses three scenarios: Low (optimistic, best case), Medium (realistic, best guess) and High (pessimistic, worst case). What if analysis was run on the schedule to determine possible impacts. This determines possible impacts at all three scenarios that will be implemented as appropriate in FY21.

Comments

- The COVID-19 impact analysis that was performed was well developed and identifies the cost and schedule impacts for all three future scenarios (Low: 6 months & $8M, Medium: 12 month & $17M, High: 18 month & $24M). There is potential that current cost and schedule contingency may not be adequate when factoring potential future impacts on the project from COVID-19 operational restrictions.

- Project was able to demonstrate tracilibility between resource estimate and baseline resource loaded schedule, however the process could be improved with more consistency (i.e. always update BOEs or specify the combination of BOE and BCRs equal tracilibility).

- The project has done a fine job with the EAC monthly practice using a manual update to track upcoming BCRs and also tracks milestones on a monthly basis (this is a good practice).

- The project may want to consider regular manual updates of remaining units in progress activities instead of automatic updates.

- The project should consider adding the COVID-19 Risk into the project's risk register.

- The project team should continue to maintain documentation as it is developed on a periodic basis so that the CD3 review team has the most recent information at the time of the review.

- There were control accounts that combined LOE and Discrete measurement for EV which could dilute the discrete activities results. The project team should be prepared to defend this practice during the CD3 review.

- Consider performing an analysis of cost of bundled procurements/year and bundling by "small procurements associated with X" instead of bundling by FY/Q, especially if cost is significant. This will allow for better float analysis and more options for moving money to meet funding constraints.

- Schedule a breakout for Cost and Schedule on Day 2 of review with time for each CAM to present a drill down of their WBS.

- Recommend that during the sub committee meetings that the project team review past recommendations and implementations are reviewed.

Recommendations

6. The Project Team should do a complete review of their resource loaded P6 schedule prior to CD3 review including the coordination of BOEs, BCRS, WADs, ETC/BAC etc. to ensure that all documents are aligned and can be easily validated between documents.

4.0 ES&H and Quality

Subcommittee: Dave Rogers*, Rich Poliak, Andrew Ackerman

Charge Questions:

- Are Environment, Safety and Health and Quality Assurance aspects being handled appropriately?

  Yes. Mature and robust processes were presented and were well integrated into the project.

- Is the project appropriately responding to and planning for impacts from COVID-19?

  Yes, with some qualifications provided in the comments.

- Is the required documentation complete at a level necessary for CD3 and have recommendations from previous reviews been appropriately addressed?

  Partial Yes. The required ES&H and QA documents have not been updated since CD2. All ES&H recommendations from previous reviews have been addressed.

Findings

- The CD3 required ISM Plan, Quality Assurance Plan, Hazard Analysis Report and Security and Vulnerability Assessment Report were posted. All are dated prior to the CD2 IPR (12/18). The QAP had been updated more recently but the newer version not posted.
- Environmental Management Systems documentation for all three labs is summarized in the ISMP with references to separate documents.
- FNAL provides on-site COVID-19 testing and 28 tests have been performed to date. Neither LBNL nor BNL provide this service.
- New "Handling of Discrepancy Reports and Non-conformances" provides the framework for Non-conformances across the entire project.
- Instrument calibration requirements managed separately by partner labs. FNAL provides some central calibration services for the site but not for all instruments or groups.
- The non-partner lab providing services, ANL, is handled as if it were a vendor per the QA Plan.
- "Functional Requirements Specification" documents the performance requirements between CERN and the project.

Comments

- In the opening presentation, discussion of how scope is shared among the four laboratories would help orient activities for the OPA reviewers and provides a chance to highlight the efforts in coordination and interface control.

- It was good to see consistent presentation from both of the partner labs, this indirectly shows good teamwork and collaboration. Partner labs are well-integrated into the Org chart and ESH and QA documents and processes.

- The Hazard Analysis Report demonstrated comprehensive review and analysis of all major complex processes to be performed.

- COVID-19 response and planning for onsite work safety seems consistent with DOE guidance, however the differences in COVID-19 PPE protocols is apparent as each lab is following local jurisdictional requirements. The major difference is in what PPE is required for close proximity work.

- The project should ensure that the impacts of the COVID-19 work protocols are carefully assessed to identify the relevant Human Performance Improvement (HPI) Error Precursors and Mitigations are included in work planning and controls implementation.

- For continued COVID-19 planning, the project should consider the limitations that may be encountered for vendor technical and QA visits.

- Overall QA approach is robust and well documented and well coordinated across all participating labs.

- Non-conformance & defects seen in coil manufacturing suggest a more proactive approach should be taken. Use of Process Failure Mode and Effects Analysis (FMEA) would be appropriate, especially in light of the yield goals being as high as they are for a still emerging technology.

- The project provided documentation of statistical process control and process capability analysis of the coil manufacturing processes demonstrating an advanced approach to quality assurance. The project should take credit for this as it is a key step in how industrialization and process stability are achieved.

- The FNAL traveler process (Vector) is a sophisticated and comprehensive electronic system at FNAL. Manual systems at LBNL and BNL are integrated into this as they are generated.

- In both the FNAL (slide 6) and BNL (slide 4) presentations on coils there were some graphs that were misleading on the actual reject rate. The number reported in the pie charts was based on both

actual and not yet performed work. This creates a different message than the information on rejects/holds and BCRs.

- The project's mitigation strategy for the coil yield issue has much emphasis on providing additional QA oversight and it is unclear how this would address this issue.
- Transportation - The analysis and data indicate a good understanding of maximum shock tolerance.
- Transportation - Early transportation data points show > 5G shocks for LARP and AUP coil shipments (slide 10), there was no explanation what was done differently to drive the performance to below 5G.
- Transportation - No studies were presented to ensure high frequency vibrations would not loosen fasteners or affect the coils in any way.
- Transportation - Humidity control is a concern but it is unclear how effective desiccant usage will be for different seasons. This does not feel well characterized.

Recommendations

7. The posted versions of the CD3 required ISM Plan, Quality Assurance Plan, Hazard Analysis Report and Security and Vulnerability Assessment Report are dated prior to the CD2 IPR (12/18). The QAP had been updated more recently but the new version was not posted. All documents should be reviewed and updated prior to IPR.

5.0 Magnets

Subcommittee: George Biallas*, Herman ten Kate and Akira Yamamoto

Charge Questions:

- Is the proposed scope of the CD3 work clearly defined and complete?

  Yes

- Are the need, technical justification, and schedule justification clearly articulated and sufficient to support the activities identified for the CD3 scope?

  Yes

- Are the relevant designs technically sound and sufficiently mature and have the appropriate reviews occurred?

  Yes

- Is the planning for major procurements, interfaces between subsystems, and integration of the project adequate to proceed with the proposed CD3 scope?

  Yes

- Have all risks relevant for CD3 scope been identified, and are the cost and scheduled contingency adequate and commensurate with the risks relevant for the execution of the CD3 scope?

  No. The risk of magnet degradation due to attempts to reach unnecessarily high fields is now being addressed by changing the Functional Specification from CERN HL-LHC. See Comments and Recommendation.

- Is the project appropriately responding to and planning for impacts from COVID19?

  Yes

- Is the required documentation complete at a level necessary for CD3 and have recommendations from previous reviews been appropriately addressed?

  Qualified Yes, except for the ultimate field requirement documentation not being consistent with the recommended agreements to be made with CERN HL-LHC.

- Is the project ready for approval of CD3?

  Qualified Yes, provided the acceptance current issue will be resolved.

Findings

- The superconducting magnet MQXFA (Q1/Q3) development, based on the US LARP, has greatly advanced under the AUP collaboration. MQXFA03, the 1st pre-series magnet, was trained up to the Nominal Current of 16,470 A plus 200 A and returned to that current with no quenches after a thermal cycle. This test demonstrated the performance required for HL-LHC operation at 7 TeV. The Ultimate Current of 17,890 A, corresponding to 7.5 TeV and required by the Functional Specification, was not examined. This strategy was used to reduce the risk of delaying the 1st cryo-assembly and test in case there was a high current failure. This cryo-assembly is necessary to meet the delivery requirement for the String Test at CERN.

- The test of MQXFA03 also verified the magnet passed ramp rate dependence, temperature margin, field quality and splice resistance. However, it could fast ramp down at 100 A/s without a quench because hardware limitations prevented ramping at the 150 A/s of the Functional Specification. This higher ramp rate can only be tested in the Horizontal Test of the Cryo-assembly, presumably after the November CD3 Review.

- AUP's intention, as of this review, is to explore the Ultimate Current capabilities in the first Pre-series Cryo-Assembly (with partner magnet MQXFA04 or MQXFA05) in a horizontal test after the CD3 Review. This pursuit of higher performance would mimic the CERN methods where only horizontal tests are utilized. See Comments and Recommendation.

- AUP reports that magnetic measurement from MQXFA03 indicates that the magnetic field is higher than design at 16,670 A by approximately the equivalent of 300 A.

- Deliverables for the magnet effort are: 20 magnets; 16 magnets for 8 Q1/Q3 Quadrupole Cryo-assemblies to be installed in the LHC tunnel; 4 magnets for 2 Q1/Q3 Quadrupole Cryo-assemblies acting as commissioning spares.

- The Functional Specification, Acceptance Criteria and Final Design Report are complete and approved by AUP and CERN HL-LHC. The Functional Specification contains the ultimate current requirement, as a threshold requirement, corresponding to 7.5 TeV.

- Quadrupole parameters are: aperture 150 mm, gradient at Nominal Current, 132.6 T/m and the peak magnetic field in the coil is 11.4 T at 16.5 kA.

- Production readiness reviews were completed for strand, cable fabrication coil parts, coil fabrication and pre-series magnets. Production readiness review for the series magnets is planned for October 2020 in anticipation of a full CD3 authorization after November's DOE CD3 Review.

- All interface documents to other parts of the project are approved and published; the CERN interface is in one document.

- The second pre-series magnet, MQXFA04, is starting testing at Brookhaven next week. The third pre-series magnet, MQXFA05, is being assembled at LBNL.

- Procurement and receipt of strand, cable and coil parts are all ahead of the quantities needed for production. Cable yield is 97% rather than the assumed 90%.

- Of 96 planned coils, 16 are completed, 7 are in fabrication, 4 are on hold (with probable 50% acceptance) and 4 are rejected.

- Because of lower yield of ~76% rather than the expected 87.5%, Baseline Change Requests added strand for 6 cables and the cabling and parts and fabrication of two additional coils.

- The major cause of coil rejection (decrease in yield) was difficulties with winding at BNL for two coils and damage from the winding machinery on two coils at Fermilab. Working on the winding machinery problem is delayed by COVID-19 response. The back-up LARP winding machine is being used instead. The BNL winding problems are mitigated by changes to winding procedure and some hardware changes. An additional coil failed because excess binder pyrolyzed and shorted the turns. This problem is being mitigated by better binder application.

- Other mitigations implemented to increase coil yield are: (1) an order of magnitude increase in gathering of coil data and subsequent statistical analysis and (2) a thorough assessment and improvement of the MQXFA Electrical QA.

- Lesson learned: Nb_3Sn Coil Fabrication technology is significantly less forgiving than NbTi technology. There are similar issues at CERN. Lessons learned and corrective actions are shared among BNL, FNAL and CERN. They perform post-mitigation risk analysis for critical equipment.

- If lower yield continues, it would lead to a 7.5 M$ use of contingency, but the project expects to meet the assumed 87.5% yield during further production because of mitigations.

- 41 other risks (33 threats and 8 opportunities) are identified for magnet manufacture and are being managed.

- The response of the Laboratories to COVID-19 has been uniform in designating the AUP production the highest priority, allowing AUP workers to be among the first to be allowed back.

- Response of AUP to COVID restrictions is that L3s and CAMs are tabulating the greater man hours needed for the work with the aim of arriving at a lower efficiency % to apply as a risk to all work. The decrease in efficiencies seen so far varies between 5 and 35%.

- The Magnet Assembly Program at LBNL is not likely to run out of parts because of a Master Agreements procurement system that allows very rapid procurement cycles after an initial contract is signed.

- Cryo-Assembly Tooling, made in Spain, is in transit. The visas for the firm's installation personnel are not being processed by the US Embassy, so AUP is attempting to use the ESTA visa waiver program for an October arrival.

- The CERN supplied Cryostat Kit for the first Cryo-assembly is in transit. Subsequent kits may be delayed by the inability of CERN personnel to travel and inspect the articles due to COVID-19 travel restrictions.

Comments

- The two main threshold acceptance requirements for the magnets apart from magnetic field quality are "stable performance at Ultimate Current at 1.9 K (corresponding to 7.5 TeV beam energy)" and "no-quench behavior at magnet ramp down rate of 150 A/s (respecting the dump time constant of a string of LHC magnets)". So far, these two requirements were not demonstrated in the pre-series MQXFA03. The first requirement of stable ultimate current would require testing all series magnets, suitable for installation in the LHC tunnel, up to a current level of 17,890 A plus some 200 A margin, say 18,100 A. This current is a huge 1,500 A more than the maximum current level achieved in MQXFA03, corresponding to 7 TeV beam energy. The test of magnet MQXFA03 was purposely stopped at this level in order not to risk the magnet for use in the String Test. The committee supports this cautious approach to maximum current level. The committee considers the second requirement, fast ramp down at 150A/s without quench, where AUP only achieved 100 A/s because of hardware limitations, to be a "soft" requirement that is not a limitation on CD-3 Approval.

- The committee congratulates the entire AUP Team for their excellent effort in building and testing MQXFA03 and achieving this Nominal Current result after a thermal cycle. It is a great start to the production program.

- The existing dipole set of the LHC seems to be limiting its energy to 7 TeV within the foreseeable future. Therefore, it is important that the MQXFA quadrupoles not be needlessly exposed to higher fields than necessary. The main driver for this whole enterprise is High Energy Physics and a failed series of quadrupoles and no Physics may be the result. It is wiser to attempt to reach higher fields in the quadrupoles that match any increase in LHC energy above 7 TeV, when that higher energy is available and able to be obtained routinely.

- Given that the technical design for the AUP MQXFA magnets is frozen since 2016, there are no options any more to increase the operational margins. We have to live with the performance of the magnets we get out of the production, provided they reach nominal operational performance. Given the widely observed vulnerability of Nb_3Sn type accelerator magnets, in general, for degradation due to production tolerances, magnet charging and magnet thermal cycles, one should avoid in a construction project any unnecessary technical risk that would cause degraded performance, leading to lost magnets, delayed AUP schedule and financial risks. Most importantly there is a risk that the entire HL-LHC project gets delayed.

- It is planned that the tests of MQXFA04 and MQXFA05 are completed before the CD3 review. Given the status of the test preparations and delays due to Covid, the schedule is very ambitious and success oriented. If both of these tests fail in terms of requirements-set or time, they can not contribute to the qualification for CD3.

- Note that the purpose of the first four magnets (the pre-series magnets and their Cryo-assemblies) is probably to participate in the CERN HL-LHC String Test and there may be an intention to not use these magnets in the LHC.

- The project has presented an underperforming yield for coil production of some 76% instead of the anticipated 87% or so. It has to be noted that on a formal basis, the yield can be referred to the contractual acceptance criteria, in particular reaching ultimate performance in a stable manner. So far NO pre-series magnet has reached the Ultimate Current of the Functional Specification and therefore the magnet yield is 0%. Instead, pre-series magnet yield could be 100% if the changes requested by the Recommendation below are implemented and the lack of attaining the 150 A/s ramp down rate is a soft requirement.

- The project decided to increase the QA effort in an attempt to increase the yield. However, it is not obvious that more QA persons on the work floor will lead to an increase in yield, as it very much depends on the nature of the problem. Thus, the effectiveness is questionable. On the other hand the project is to be commended that they also used another path. They commissioned a skilled engineer from another project, that involved production, to help find flaws in production tooling and work floor procedures. The other additional QA effort they are employing is also very useful, they are monitoring the production, gathering selected production parameter data and using statistical analysis to feedback to the production process.

- "COVID restrictions may have an impact" on other than efficiency because training is more difficult and there is less on-floor supervision. On the other hand, individual work may be more carefully done. The effect on yield is not clear.

- Unlike the present AU Plan, the maximum excitation of magnets should be first demonstrated with the magnet alone in the vertical test (confirming the safe magnet excitation), and the final test with cryostat in the horizontal test should be limited below the maximum excitation realized in the vertical test. Degradation or failure found at the horizontal test stage would be a waste of time materials and manpower. We, as a community, are learning important critical experiences from the 11 T dipole and MQXB prototype test at CERN. We should seriously take this learning into the AUP future direction/plan as well.

- The QA/QC, in particular, for the Quench Protection Heaters, impregnated together with the coil structure, remains a critical issue. The project is performing a careful, visible inspection with photographic records of each coil. This can add to minimizing the risk due to bubbling/delamination of the heater layer from the main coil structure by being able to detect it with another pair of eyes, looking at the photographs, off-line. The photographs may also be helpful information to diagnose any unpredictable incident.

- Putting all the coil and magnet shipping under one magnet scientist is a great idea. Shipping is now subject to the same quality program as other parts of the project and has room for expanded professionalism. Examples are the finite element analysis of shipping configurations and the analysis of one coil subject to detected excessive loads while analysis showed it had experienced only limited micro strain and is therefore acceptable.

- The distribution of the AUP Program throughout the country allows large portions of the project to continue if there is a local shut down of 2 to 3 months due to COVID-19.

- Reiterating the comment from the executive summary, once the AUP Project completes its deliverables, the project can wind down. However, it is anticipated that experts working on AUP should stay engaged (to work with CERN) until the components (in particular for the Nb3Sn magnets) are operating in the HL-LHC. This will require a funding source outside the current AUP Project.

Recommendations

8. Prior to the CD3 Review, obtain a statement from CERN HL-LHC management that re-defines the Ultimate Quadrupole Current Requirement to be the Objective Field Gradient Requirement and redefines the Nominal Current plus margin to be the Threshold Field Gradient Requirement.

6.0 Crab Cavities

Subcommittee: Mike Kelly*, Peter Ostroumov, Anne McEwen

Charge Questions:

- Is the proposed scope of the CD3 work clearly defined and complete?

  Yes. Acceptance criteria documents for cavities need to be released.

- Are the need, technical justification, and schedule justification clearly articulated and sufficient to support the activities identified for the CD3 scope?

  Yes, the cavities and ancillaries appear to meet CERN technical and schedule needs. High-level technical requirements should be presented clearly and from the outset.

- Are the relevant designs technically sound and sufficiently mature and have the appropriate reviews occurred?

  Yes, designs are supported by extensive simulations and experimental studies.

- Is the planning for major procurements, interfaces between subsystems, and integration of the project adequate to proceed with the proposed CD3 scope?

  Yes, integration within the AUP work scope is adequate to proceed. Integration of cavity deliverables with partners at CERN and TRIUMF needs additional work.

- Have all risks relevant for CD3 scope been identified, and are the cost and scheduled contingency adequate and commensurate with the risks relevant for the execution of the CD3 scope?

  Yes, risks relevant to AUP scope are reasonably well identified and are mitigated. Please see the comment on additional risks for the CERN HL-LHC project.

- Is the project appropriately responding to and planning for impacts from COVID-19?

  Yes, but it is possible that additional COVID-19 mitigations could be taken. Please see the comments.

- Is the required documentation complete at a level necessary for CD3 and have recommendations from previous reviews been appropriately addressed?

  Yes, for the most part. Please also see the comments.

Findings

- The AUP crab cavity deliverables include ten “fully dressed” RF dipole (RFD) crab cavities and RF ancillaries. The cavities will later be installed into five cryomodules at TRIUMF and after acceptance of the AUP deliverables by CERN. Two additional cavities will be “hot spares”.
- Other AUP deliverables include test samples and documentation of interfaces
- The term “dressed cavity” refers to the niobium cavity with the integral helium tank and internal magnetic shield. RF ancillaries refer to the higher order mode dampers and pickup probes. These ancillaries will be built, qualified and installed onto the cavity ports as part of AUP work.
- AUP cavities are planned to be delivered to CERN as five pairs. The first planned delivery is in June 2022 and the last delivery is planned for May 2024.
- There are 27 (15+12) months of float on cavity delivery with respect to the CERN HL-LHC schedule.
- The fabrication plan for the cavity helium tank is under development and potential vendors are being studied.
- There are three open recommendations from previous reviews. These are recognized and being acted upon.
- The cost and schedule performance for cavities is close to that of the project plan. Cavity activities are just over 20% complete in terms of project earned value.
- FNAL crab cavity hazards have been included in an AUP Hazard Analysis Report. Activities such as cavity processing and testing are covered by local procedures at the respective institutions and facilities.
- The dressed RFD cavities will be built per CERN Engineering specifications EDMS NO1389669 including pressure vessel requirements.
- A detailed cavity fabrication plan with QA steps has been developed and was presented.
- AUP will provide CERN Manufacturing & Inspection Plans (MIP). The MIPs describe the manufacturing and inspection steps for AUP deliverables, including dressed RFD cavities.The MIPs for the dressed cavities is presently planned to be completed after the planned November DOE CD3 review.
- Acceptance of bare cavities as they move through processing and testing will be performed by AUP in consultation with CERN.

- Fabrication of the first RF dipole prototype cavity from Zanon is complete and expected to arrive at FNAL in August 2020. The frequency is approximately 500 kHz off of the nominal value. The specified window for acceptance is plus or minus 150 kHz. The second prototype is planned to arrive later in Fall of 2020.

- Fabrication of the first prototype cavity at Zanon required approximately two years to complete. Approximately 4 months of delay were due to AUP requested changes. Another six months of delay was due to COVID-19 impacts.

- The order for the two AUP pre-series cavities has been placed.

- After planned delivery of the dressed cavities from Fermilab to TRIUMF, and after official acceptance by CERN, the flanges on the beam ports and fundamental power coupler port will need to be opened before assembly into the cryomodule.

- CERN and Daresbury are, relatively separately from the AUP cavity work, building and assembling two RF Dipole cavities and a cryomodule that are planned to go into the SPS in 2022.

- Two sets of planned acceptance tests for the jacketed cavities with the HOM antennas installed are written down in documents referred to as Acceptance Criteria Parts A and B. The former covers testing at Fermilab and is in the final stages of approval. The second covers testing at TRIUMF before handoff to CERN and is in draft form. Both are planned to be accepted by CERN and released before proceeding to CD3.

- AUP responsibilities extend through the cold testing at TRIUMF of the as-delivered cavities

Comments

- The AUP team, including collaborators at Fermilab, BNL, JLab, SLAC , Berkeley, and ODU, is highly experienced, has a sound plan and is making strong progress toward delivery of the AUP cavity scope.

- Hi Lumi plans to use this exciting and world-unique superconducting cavity system as an important technical and performance upgrade to the largest accelerator in the world.

- Placement of the prototype, and pre-series fabrication contracts with the same vendor as for the production cavities was a recommendation from a 2017 review. This is consistent with lessons learned from other projects, and appears to be a wise choice.

- Due to the COVID-19 situation the AUP should consider hiring an expert local to the cavity vendor to help with oversight and to monitor progress.

- The absence of integrated testing for the prototype jacketed cavity with fundamental RF coupler and tuner prior to the CD3 poses significant technical risk for the CERN HL-LHC project. To reduce the risk, AUP should consider mitigation strategies. The reviewers suggest the possibility of shipping

the first prototype cavity to CERN to integrate into the two-cavity cryomodule to be tested at the SPS.

- Another integrated testing opportunity might be afforded by reallocating a portion of the 27 (15+12) months of float for cavities with respect to the CERN HL-LHC project and use this to perform testing. AUP should discuss this possibility within the framework of the HL-LHC collaboration.

- There is a small risk in proceeding to production of bare niobium cavities without having tested a jacketed cavity. There is an opportunity to learn from the CERN test of their jacketed RFD cavity planned for December 2020. The AUP team should take advantage of this.

- The two cavity prototypes will elucidate details of niobium forming, drawing, welding and chemical processing. This should help ensure that the pre-series cavities are of high quality, and representative of the production cavities. The AUP should attempt to apply all quality controls and perform needed steps so that the pre-production cavities may be suitable for installation into cryomodules.

- The approximately one half MHz frequency offset for the first prototype cavity is mildly concerning. The desired frequency tolerance is ±0.15 MHz. The first prototype should be analyzed carefully to identify the source of the frequency deviation and correct this for the second prototype.

- If the second prototype cavity cannot be brought onto frequency, then work on the two pre-series cavities should be paused and the tuning procedure should be more carefully reviewed.

- All specification, interface and acceptance documents except the Manufacturing and Inspection Plan (MIPs) for the dressed cavities will be released prior to the DOE CD3 Review. It would be preferable to release the MIPs for the dressed cavities before CD3 as well.

- The status and plans of the work to be done by the AUP team at TRIUMF in the Acceptance Criteria, Part B should be completed as soon as possible and signed off and released by AUP. The close participation of TRIUMF with CERN and Fermilab collaborations is encouraged.

- The flanges that require disassembly from the AUP as-delivered cavities at TRIUMF could lead to particulate contamination in the cavities. The AUP team should discuss this issue with CERN and develop a plan if indicated.

- For CD3 we encourage the team to clearly explain the deliverables, not just the hardware, but also the testing and qualification plans early in the presentations. Since the ultimate goal is to deliver the AUP scope so that it is successfully used in the CERN HL-LHC project, the team is encouraged to orient the reviewers early with a high level overview of both AUP and HL-LHC goals. The plan for the cavities after leaving Fermilab for TRIUMF has some complexities. We suggest that this be elucidated clearly and early in the presentations.

- We commend the AUP team on the strong technical plan and good performance to date on cavity work.

Recommendations

9. Complete and release the Acceptance criteria, Manufacturing and Inspection Plans for the bare cavity and ancillaries and Functional Specification Drawings prior to the CD3 review.

10. Work with CERN to develop a plan that incorporates AUP team members into the work and planning for activities at TRIUMF following those described in Acceptance Criteria Part B. Start this as soon as practicable and complete before the CD3 review.

Appendix A - Charge

Director's CD-3 Review of HL-LHC Accelerator Upgrade Project
July 28-30,2020

Fermilab

Fermi National Accelerator Laboratory

Date: **June 8, 2020**
To: Doug Glenzinski, Chief Project Officer
From: Nigel Lockyer, Director
Re: Director's CD-3c Review of HL-LHC Accelerator Upgrade Project

Message:

Please organize and execute an assessment on July 28-30, 2020 that will determine the readiness of the HL-LHC Accelerator Upgrade Project (AUP) to proceed to CD-3c for the approval to continue production of MQXFA Magnets, RFD Dressed Cavities and LMQXFA Cold Masses. The assessment should address the following questions:

1. Is the proposed scope of the CD-3c work clearly defined and complete?
2. Are the need, technical justification, and schedule justification clearly articulated and sufficient to support the activities identified for the CD-3c scope?
3. Are the relevant designs technically sound and sufficiently mature and have the appropriate reviews occurred?
4. Is the planning for major procurements, interfaces between the subsystems, and integration of the project adequate to proceed with the proposed CD-3c scope?
5. Is the baselined resource-loaded schedule still adequate to serve as the performance baseline for the CD-3c scope?
6. Have all risks relevant for the CD-3c scope been identified, and are the cost and schedule contingency adequate and commensurate with the risks relevant for the execution of the CD-3c scope?
7. Does the project understand its dependencies on outside resources such as international collaborators ?
8. Are Environment, Safety, and Health and Quality Assurance aspects being handled appropriately?
9. Is the project appropriately responding to and planning for impacts from COVID19?

10. Is the required documentation complete at a level necessary for CD-3 and have recommendations from previous reviews been appropriately addressed?
11. Is the project being well managed, and is the project team being properly supported by the participating laboratories and Fermilab, in particular?
12. Is the project ready for approval of CD-3c?

The Committee is asked to present a draft of their answers to these charge questions and recommendations at the close of the assessment, and a final report within three weeks.

Nigel S. Lockyer
Director of Fermilab

Appendix B - Review Committee

Director's CD-3 Review of HL-LHC Accelerator Upgrade Project
July 28-30,2020

Chair
Rich Stanek (FNAL)

SC1 - Project Management
Mark Palmer (BNL)*
Steve Nahn (FNAL)

SC2 - Cost & Schedule
Jeff Deal (PNNL)*
Marianne Bossert (FNAL)
Josh Byrd (PNNL)
Laurie Casarole (BNL)

SC3 - ES&H and Quality
Dave Rodgers (LBNL)*
Rich Poliak (SLAC)
Andrew Ackerman (BNL)

SC4 - Magnets
George Biallas (TJNAF)*
Herman Ten Kate (U. Twente)
Akira Yamamoto (KEK)

SC5 - Crab Cavities
Mike Kelly (ANL)*
Peter Ostroumov (MSU)
Anne McEwen (TJNAF)

Observers
Adam Bihary (DOE-FSO)
Jerry Kao (DOE-FSO)
Simona Rolli (DOE-HEP)

*Sub-committee lead