Fermilab

Final Report

Director's CD-3c Review of the Mu2e Project

April 19-21, 2016

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1.0 Executive Summary

A Director's CD-3c Review of the Mu2e Project was held on April 19-21, 2016 at Fermilab. The focus of this review is readiness of the project to proceed to the DOE CD-3c review scheduled for June 14-16, 2016.

The Mu2e Project will construct a new facility to enable the world's most sensitive search for charged lepton flavor violation by searching for the conversion of a muon to an electron in the field of a nucleus. Mu2e will be ~10,000 times more sensitive than the world's current best limit. The Project consists of modifications to the existing Fermilab accelerator complex, construction of a new external beamline, construction of a new detector hall on the Fermilab site and construction of a new detector to search for muon conversion. The detector includes a complex system of superconducting solenoids, a collimation and charge selection system for producing the world's most intense low-energy muon beam, a low-mass tracking detector and crystal calorimeter operating in vacuum, and a cosmic ray veto, all read out by a unified DAQ.

Overall design is quite advanced and reported to be 85% complete using criteria detailed in the *Design Completion Definition Document*. The design is sufficiently mature to continue fabrication and procurement on areas underway. For those elements of the design that are still not finalized, the project can show that there are no major issues that need to be addressed and that they are on a clear path to a final design.

The project has been effective in using a series of design reviews and oversight committees to reach this stage. Appropriate project controls practices have been underway for over a year. Activities authorized at CD-3a, and CD-3b are progressing well on cost, schedule, and scope. Change control is in force across the project. Funding plan appears sufficient to execute the project. Contingency use to date has been appropriate with 36% remaining on cost to go.

The project team, comprised of Fermilab staff and collaboration members, and the management team is excellent and is functioning well. Transition to operation planning is already well underway for both the near and long term needs, and a strong team with broad and deep expertise has been formed to execute the system integration process. There was excellent response by project team to the committee's questions before and during the review.

The availability of resources, especially cryo engineering and design, has been an issue and some designs are behind schedule. The most recent issues have been addressed and satisfactory progress has been resumed. As the project progresses the laboratory and project should anticipate resource stresses emerging in other areas also. Continued attention by laboratory management will be required over the next few years to assure needed resources are available to the project

The Project is ready for the DOE CD-3c IPR.

2.0 Introduction

A Director's CD-3c Review of the Mu2e Project was held on April 19-21, 2016 at Fermilab. The focus of this review readiness of the project to proceed to the DOE CD-3c review scheduled for June 14-16, 2016.

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2.0 Technical Systems

2.1 Accelerator Systems

Subcommittee: Keith Gollwitzer, Paul Derwent, Jim Hylen

Charge Questions:

- Is the design sufficiently mature so that the project can continue with procurement, fabrication, and construction?

Yes, the design is sufficiently mature to proceed to CD-3c review.

- For those elements of the design that are still not finalized, has the project shown that there are no major issues that need to be addressed and that they are on a clear path to a final design?

Yes.

- Have recommendations from prior independent design reviews been adequately addressed?

Yes, some have been closed out while work to address the others is ongoing.

Findings

- The Accelerator L2 has had 8 Design Reviews resulting in 42 recommendations; 13 of the recommendations have been addressed and closed.

- Since CD-2, the Controls WBS and Target Station WBS had scope moved to the Conventional Construction WBS associated with the installation of building controls (WBS 475.03.04.05 Building Controls) and the proton beam absorber (475.03.04.04 Absorber Fabrication).

- Interfaces between Accelerator L3 tasks are defined. Interfaces with other Mu2e L2 tasks are not completely known and/or documented. For example, within the documentation there is mention of only two accelerator signals being provided to outside groups, timing signals; there could be the desire to know beam intensity, spill quality and other beam parameters.

- The total proton beam requirements for the experiment combines the physics requirement (3.6e20) and recent request for calibration (1.1e20). With the current assumptions on the complex performance, it is a little more than 4 years to reach this total.

- There is 1 critical procurement (according to the project definition) in the Accelerator WBS: the procurement of the heat and radiation shield (HRS).

- Due to RAL work, the project has gained confidence in the ability of the radiatively cooled target to meet the requirements, and has assigned very low probability to having to fall back to gas or water cooling.

- Since CD-2, the Target Station WBS has increased scope to include a new antiproton absorber. A foil to absorb antiprotons will be placed near the junction of the PS and TS. The added scope entails that the remote handling system has to be able to inspect and replace the antiproton absorber.

- The design of the window remote handling, which had not been shown at the previous design review, has now been finished. Thus there is remote handling design for all three components (window, target, foil) that require it. Prototyping of this equipment will start this summer.

- The team noted several instances where the Design Reviews gave very valuable recommendations: for example, HRS and PS interface (PS able to support the HRS), resonant extraction fault matrix, LLRF linked to Recycler Reset, and testing of profile monitor in magnetic field.

- The location and usage of profile beam monitors in the M4 are not well defined.

- The Accelerator will have at least 17 Construction Readiness Reviews (CRR) between August 2016 and October 2018. With one exception, prototyping will occur before the CRR; the building of the full-size prototype of the electrostatic septum will occur after the CRR.

- An Accelerator Technical Oversight Committee has been formed, with four members (two internal to FNAL and two external). The committee has yet to meet.

- The Accelerator improvements for Mu2e are done as part of an integrated plan (the Muon Campus) to deliver beam for both the g-2 and Mu2e experiments. There is a mix of Accelerator Improvement Projects, General Plant Projects, and DOE O413.3 projects to bring this plan to completion. Oversight is provided by Accelerator Division and the Directorate. The project uses interface milestones to track progress on the external pieces. The same people are doing similar tasks for each project and form natural interfaces. There is a muon campus installation coordinator for the accelerator enclosures (up to the PS room).

Comments

- Of the 42 recommendations, 29 are still listed in progress. The project has responded well and is addressing all of the recommendations. The team members should be commended for their embrace of this process. The L2 and others commented on how useful it has been.

- The BCWS for the Accelerator WBS shows a distinct change in slope (by about a factor of two) in August 2016, coinciding with planned CD-3c approval. While the L2 is confident the resources are available to meet the accelerated schedule, it bears watching. Labor resources and spending rarely ramp that quickly.

- The Controls WBS and Target Station WBS had scope moved to the Conventional Construction WBS associated with the installation of building controls (WBS 475.03.04.05 Building Controls) and the proton beam absorber (475.03.04.04 Absorber Fabrication). These changes

are understood and justifiable. Both of these are part of the CD-3b scope and are proceeding well.

- The Accelerator interface documentation to other parts of the project should be improved.

- During the breakouts, the L3s were asked if they had the resources to complete on time and on budget. While all answered positively, there were several that expressed concerns about specific resources who have other responsibilities or are not assigned. A specific instance is a motion controls engineer in support of remote handling. The L2 and AD management will need to stay in close communication to stay in front of conflicts before they impact the project.

- Since the installation of the target is after the end of the project, there is still time to go through the prototyping of the target and remote handling equipment, then do the CRR and construction.

- The installation schedule of the M4 beam line has four phases and occurs over four years. The phases are dependent upon the muon campus operations. These phases are not related to other mu2e installation phases. The installation plan documentation consists of the P6 schedule and BOEs making it hard for an outsider to determine the schedule.

- The response to recommendation 6.Beam,Inst,Ctrls #5 "Verify that activation of the LCW flowing through the HRS will not introduce radioactive contamination issues when that water is mixed with the general LCW system" is incomplete. It currently only addresses Tritium. Creation of other radio-nuclides should also be addressed.

- 7 of the 17 listed Accelerator Construction Readiness Reviews are scheduled to occur on the same day. It is hard to hold so many reviews at once.

- While there is time in the schedule for the HRS procurement, the procurement plan does not exist. As this is a critical procurement ($1.9M) with a long delivery period (~1 year), the project needs to develop the plan. The solenoid procurements may be a good model.

- Although not on the critical path, the arrival of the HRS has a 5 day float. If late by more than a week, then the installation of the PS will be delayed. There is a ~6 month gap between the HRS bid acceptance until funds are available.

Recommendations

1. Complete the interface documentation for the DOE CD-3c review.

2. Schedule all Accelerator Construction Readiness Reviews with realistic dates.

3. Consider investigating how to proceed with the HRS procurement earlier.

2.2 Solenoids

Subcommittee: George Biallas, Alan Bross

Charge Questions:

- Is the design sufficiently mature so that the project can continue with procurement, fabrication, and construction?

Yes. The Design of the Solenoid System is very mature. The project should continue with funding the Production Solenoid (PS) and Detector Solenoid (DS) fabrication and start funding the remaining sub-system procurements and construction.

- For those elements of the design that are still not finalized, has the project shown that there are no major issues that need to be addressed and that they are on a clear path to a final design?

Yes. The concepts are well formulated for those elements that are not fully designed. Risk of substantial change during the remaining work is small. The system is on a clear path to final design.

- Have recommendations from prior independent design reviews been adequately addressed?

Yes. All recommendations from prior reviews are adequately addressed. Recommendations for the Transport Solenoid (TS) are fully retired. Recommendations for PS and DS and the remainder of the system (Cryo, Power Supplies and Quench Protection) are under active resolution and many are retired.

Findings

- The procurement philosophy for these solenoids is to have industry make what they do best and Fermilab do what it does best. All three solenoid procurements are in place. This process was aided by using input from the Acquisition Oversight Committee.

- Industry is making the 52 coils (in 14 modules) for the Transport Solenoid (TS). Fermilab will do the magnetic tests, fabricate the rather complex cryostats and do the final assembly.

- A single vendor is contracted to design/build both the Production Solenoid (PS) and Detector Solenoid (DS). These are simpler, more conventional solenoid designs and we judge the fact that one vendor, building both magnets, is not a risk because of the vendor capability.

- Credible plans are in place for procuring the remaining elements of the solenoid system. A series of 5 independent design reviews addressed these remaining elements of the system. In addition the Fermilab Procurement Department should be credited for the creative ways they have structured these contracts.

- Overall, the Solenoid System design is about 85% complete. The magnet designs are at higher completion states.

- The TS Module design is 100% complete. The prototype tests were successful and a competent European vendor appears to be on track to deliver the coil modules on time, starting at the end of 2016 and ending in 2017.

- The Mu2e Group took on the task of magnetically testing the individual coil modules of the TS. The pre-production prototype module was successfully tested in a large cryostat located in CHL. Mu2e decided to move the SOLTF test cryostat to HAB (the old CDF) building and to re-establish the CDF Cryo-plant for test of all the production modules, adding a 1.5 $M increase in system cost, coming out of contingency.

- The PS/DS designs by the vendor are 95% complete. The vendor is meeting milestones. An extensive review process finished with 24 non-major recommendations to the vendor early in the month of April. The Construction Readiness Review (CRR) for PS/DS is scheduled for the Fall 2016. This event drives the project critical path. Other CRRs for the System are scheduled to occur in a timely fashion and do not drive the project schedule.

- The vendor for the PS/DS announced that they are moving magnet production from a facility that is very experienced in making superconducting magnets to a relatively new facility in another part of the country. The facility has a state of the art building with exceptional machining and fabrication support facilities, but with "touch labor" that only have experience in building room temperature magnets.

- The vendor is mitigating this lack of experience by promising that a rotation of project engineers from the original team will be at the new facility full time for a month at a time, with one week overlap at the rotation. Similar plans by Fermilab are in place for coverage at the new facility. In addition, the project is negotiating for three mitigations that are beyond-contract-scope of the contract, (1) winding additional model coils, (2) Vacuum Pressure Impregnation tests (VPI) and (3) several practice insertions of model coils into hot, expanded aluminum support shells. These mitigations, if enacted, will result in a 4 to 6 month schedule delay.

- PS/DS cold tests have to be done at the original facility after a cross-country shipment.

- Lagging at 50% completion level, are two cryogenic engineering/design tasks that are the cause of schedule variance: (1) the cryostat for the TS and (2) the four Cryogenic Feedboxes for the solenoids. The system reports that the required resources are now available and that these non critical path tasks will be done on time. Management is aware that keeping the resources on this task is vital.

- The power supply and dump resistor system design is at 90% completion, but is now on hiatus. The design of this system, along with that of the quench protection system, indicates that the 100 MJ stored energy in the solenoids can be dissipated safely. Further work is scheduled for start up again in about a year.

- Instrumentation and Control, Ancillary Equipment, Integration, Installation, Commissioning Magnet Mapping and Radiation Monitoring and RRR Recovery are well defined and are at a high level of design or planning completion.

- Interfaces, risks, and ES&H issues are identified and appear under control.
- QA/QC plans are implemented well.
- The Solenoid schedule remains consistent with the baseline schedule approved in March 2015. Costs rose ~3 $M out of 91 $M with ~1.5 $M from the scope increase mentioned above.
- Production of the superconductor for the PS is scheduled for delivery in November of 2016 after a multi country manufacturing cycle. Superconductor is needed by February of 2017. This float can easily turn into a delay if import/export issues that were experienced in the past occur again.

Comments

- There may be a potential quality or delivery problem looming for the PS/DS with their Vendor moving magnet production from a facility that is very experienced in making superconducting magnets to a relatively new facility with touch labor that only have experience building room temperature magnets.
- Since superconducting magnet vendors have such a checkered history of not delivering on time, when a vendor misses a deadline, immediate mitigation is necessary.
- It is vital that the cryogenic engineering /design resources continue to be available to finish the design of the TS Cryostat and the 4 Cryogenic Feedboxes.
- Careful attention must be paid to the delivery schedule for the PS superconductor.

Recommendations

4. The beyond-contract-scope mitigations for potential quality or schedule problems of the PS/DS mentioned above should be added to the contract.
5. Increase vendor visits, and bring along a procurement officer, if a significant delay is experienced in any magnet delivery.

2.3 Muon Beamline

Subcommittee: Rich Andrews, Rick Tesarek

Charge Questions:

- Is the design sufficiently mature so that the project can continue with procurement, fabrication, and construction?

YES: The designs for the muon beamline are overall 65% complete. The risk of significant changes to the designs is low. Procurement, fabrication and construction can proceed as planned.

- For those elements of the design that are still not finalized, has the project shown that there are no major issues that need to be addressed and that they are on a clear path to a final design?

YES: The designs have no significant technical challenges. Some additional input is needed from sources external to the muon beamline to finalize the design. A written plan exists to obtain those additional inputs and includes the scope and resources needed to complete the design.

Have recommendations from prior independent design reviews been adequately addressed?

YES: Recommendations from older reviews have been addressed. For reviews that have occurred only recently, we have seen reasonable progress toward addressing those recommendations.

Findings

- The muon beamline subproject touches all other groups but many tasks within the subproject occur late (2018-2020).
- The schedule for the muon beamline has considerable float to completion. Their schedule has many serial tasks. Slippage of one or more installation tasks could delay the project completion and represents a high risk.
- The muon beamline design efforts has been resource limited in engineering and design/drafting
- Only the vacuum system has had an external design review. The design of other components are scheduled for construction readiness reviews.

Comments

- Highly competent team designing the muon beamline. This is a complex system with many interfaces to all other systems in the project. The team was very responsive to questions.
- Designs for all subsystems are at an advanced stage, though not complete and ready for fabrication. There are no significant technical challenges that would inhibit the completion of final designs.
- The muon beamline vacuum subproject should work to complete the piping and instrumentation diagram (P&I) and failure mode and effects analysis (FMEA) for initial components in 2017.
- The vacuum subsystem should consider expanding the designer/drafter team to facilitate timely production of drawings for discussion, review and fabrication.
- The COL3u/d collimators move and the motion control will be inaccessible for much of the life of the experiment. Tests should be performed as early as practical to ensure the reliable operation of the rotation mechanisms over the life of the experiment.

- The muon stopping target monitor is an important component of the experiment. Radiation damage to the germanium detector can compromise performance of the detector by broadening the capture lines that serve to measure the number of stopped muon.

- Shielding simulations continually improve and iterations between shielding design and simulation can become an infinite loop. Eventually one must make a decision on the design for the shielding prior to procurement. Determine a sufficiency criteria (what's good enough) to achieve an acceptable design prior to procurement of the shielding blocks.

- Installation of some shielding blocks will requires specialized fixturing. Design of the handling fixtures should be included in the shielding installation task.

- The cables and services that support the detectors will be routed in the limited space between the muon beam stop and vacuum spool piece wall. A physical model of the cables and services in this limited space should be made as early as practical.

Recommendations

6. The project should evaluate the effects of radiation damage on the muon stopping target monitor detector and effectiveness of the annealing cycles.

7. Flesh out the design of the muon stopping target monitor, the sweeping magnet and collimators.

2.4 Calorimeter, Cosmic Ray Veto

Subcommittee: Deborah Harris, Adam Para

Charge Questions:

- Is the design sufficiently mature so that the project can continue with procurement, fabrication, and construction?

  The design is sufficiently mature that the project can continue as planned with the testing, followed by review and procurement, fabrication, and construction.

  Calorimeter system: Calorimeter system: The crystal size and specifications are determined and vendors are being qualified. SiPM's have been specified and vendors are being qualified. The project is ready to launch procurement for the pre-production phase to rank different vendors. Final procurement of crystals and photosensors will follow a dedicated Construction Readiness Review, scheduled for April 2017. The remaining calorimeter fabrication and construction will only proceed after a vertical slice test followed by the Construction Readiness Review.

  Cosmic Ray Veto: WLS fiber diameter is still kept as something that could change, but other than that the design seems very mature. Again, procurement, fabrication, construction will only proceed

after a vertical slice test followed by a construction readiness review, which is scheduled to take place in July 2017.

- For those elements of the design that are still not finalized, has the project shown that there are no major issues that need to be addressed and that they are on a clear path to a final design?

Yes for both the calorimeter and the cosmic ray veto system.

- Have recommendations from prior independent design reviews been adequately addressed?

As of this review, all recommendations from the CD-2 review for these two subsystems have been addressed appropriately.

For the calorimeter subsystem, the independent design review took place in February 2016 and there were 13 recommendations. The project is starting to investigate the issues raised but in 2 months the recommendations cannot all be completely addressed.

For the cosmic ray veto system, the independent design review took place in March 2016, and there were three recommendations, two of which have been addressed in full, and the last recommendation, which involves additional simulations, is being addressed.

Given the short times allotted for the CD-3b Director's Review, we note that the Independent Design Reviews are very helpful and allow for much more detailed technical investigation by the reviewers. We commend the project team for their responses and actions that result from the Independent Design Reviews.

Findings

- Calorimeter: The design choice of CsI was made about 6 months before this review.
- Calorimeter: Pre-prototype versions of the calorimeter waveform digitizer and front end electronics have been tested, and the design is estimated to be 60% complete.
- Calorimeter: A relatively novel method of biasing three SiPMs in series is being adopted following the solutions adopted by the MEG experiment. The vendor specification of the SiPM is expected to include a module consisting of two parallel series of three SiPMs in each series.
- Calorimeter: Studies of the neutron-induced radiation damage to the SiPMs have been conducted and lead to the decision to cool down the SiPMs to 0C. The cooling system was implemented into the design of the calorimeter.
- Calorimeter: The project team described in detail the crystal specifications, the test beam measurements they have already made, and plans for prototyping and qualifying crystal and SiPM vendors, which include both cosmic ray tests and radiation damage tests. The project is planning to

spread the effort out across many institutions while minimizing the shipping of the crystals themselves.

- Calorimeter: A detailed calibration plan was described, which involves both a liquid source that is pumped into tubes very close to the crystals, as well as a laser calibration system. Time did not allow for discussion of other (beam-related) calibration strategies.

- Cosmic Ray Veto: The project team described in detail the module assembly plans, as well as the pre-production plans that are scheduled to occur before procurements begin. The team also described the radiation damage tests that will be performed on the SiPM's.

- Cosmic Ray Veto: The project showed that the deadtime introduced as a result of beam induced backgrounds in the CRV is negligible.

Comments

- Calorimeter: An impressive amount of work has been done to specify the crystals, SiPM's, and design details, and to prepare for timely delivery of this subsystem.

- Calorimeter: Given the early stage of design of the waveform digitizer, it does not seem likely that the full component test, if it is to be done by April 2017, can include the final version of either the waveform digitizer or the front end electronics.

- Calorimeter: The serial biasing of the SiPMs has a major advantage as it minimizes the capacitance and consequently improves the response time of the detector. The consequences for the energy resolution and the overall robustness of the system need to be studied and understood for the specific application to the mu2e experiment. In particular one should understand the implications of the serial biasing for the case of potentially different radiation damage to the SiPMs in one serial chain.

- Calorimeter: Extensive studies of the mitigation of the radiation damage to silicon detectors by lowering the temperature of sensors indicate a need to keep them at lower temperature at all times, not allowing the warm-up to the room temperature. It is not clear if the same requirement is important for the SiPM case, but a major improvement of the design of the cooling system may be necessary if the answer is affirmative.

- Cosmic Ray Veto: the project team has been careful to learn from past experience for module assembly, from details of the assembly procedure to specifications for the storage locations. There have not been many aging studies done on the complete assembly (scintillator plus fiber) for this configuration, so there is currently a sizeable uncertainty on the expected light loss per year.

- Cosmic Ray Veto: Radiation damage to the photosensor is predominantly caused by low energy neutrons, it is desirable to conduct the radiation damage studies with the final packaging to include potential contributions from other materials.

Recommendations

8. Calorimeter: We recommend that the project consider appointing an oversight committee for the Calorimeter, similar to the oversight committee already in place with the Cosmic Ray Veto subsystem.

9. Calorimeter: Studies of the performance of the crystals and SIPMs with serial biasing have been carried out but the implications of the serial biasing have to be better understood. We recommend that the project perform more detailed bench tests of the serial biasing of the SIPMs, even if this might merely validate the MEG studies.

10. Calorimeter: We recommend that the project continue to plan the crystal and SiPM procurements after the quality assurance and radiation hardness tests of these components, and a Procurement Readiness Review is conducted, or there has been validation by the Oversight Committee recommended above.

11. Cosmic Ray Veto: The project should try to incorporate as much as possible into its vertical slice test: not only the scintillator and the SiPM's, but also the aluminum, the electronics, and the DAQ.

12. Cosmic Ray Veto: The project should consider doing aging studies to reduce the uncertainty on how much the light yield of the scintillator plus fiber assemblies will decrease per year. This will ensure that the light yield of the planned design meets the specifications at the beginning and end of the run.

13. Calorimeter and Cosmic Ray Veto: the project should continue the plans they have described for crystal and SiPM vendor qualification, prototype construction, and prototype testing in test beams, cosmic rays, and source tests.

2.5 Tracker, Trigger, DAQ

Subcommittee: Kevin Pitts, Tom LeCompte, Andrew Norman

Charge Questions:

- Is the design sufficiently mature so that the project can continue with procurement, fabrication, and construction?

Yes.

- For those elements of the design that are still not finalized, has the project shown that there are no major issues that need to be addressed and that they are on a clear path to a final design?

Yes.

- Have recommendations from prior independent design reviews been adequately addressed?

For the tracker, the recommendations have been addressed or are being addressed with ongoing or planned work. For TDAQ, this committee has reviewed the recommendations and the responses and believes that recommendations have either been satisfactorily addressed, or are no longer relevant to the current requirements and designs of the project.

Findings

- A detailed technical plan for construction, both mechanical and electrical, was shown for the Tracker. Most technical decisions are made, and will be tested with the next prototype ("Version 2.5"). Some areas did not have final design choices in place, such as the ADCs, but decision points have been identified.

- The Tracker group presented a production plan. The QA/QC component lacked specificity and well-identified go/no-go thresholds.

- A new position of Trigger Coordinator has been created and filled.

- The TDAQ development effort has a projected need of approximately 6 uncosted scientific personnel (3 FTE) starting in FY17/18 to work on the development of tracking and trigger algorithms central to the performance of the TDAQ filter chain. This effort has not been identified or associated with a specific institution which will assume the responsibility for these contributions to the project.

- The TDAQ development effort requires specialized technical resources in the form of firmware engineers. This effort has been reflected in the current effort profile for FY17/18, is smaller in FY19/20 and is zero during the critical commissioning and integration periods of FY21.

- The TDAQ system plans to provide a local disk cache sufficient to store 48 hours of detector data within their acquisition environment (prior to recording to archival storage). This amount of local storage will allow the experiment to tolerate a sustained outage of facilities downstream of their DAQ (networking or archival tape systems) without interruption of data taking for at least 24 hours.

- The current procurement and deployment plans for the COTS TDAQ hardware place it into service in FY18/19 as required for full integration and testing with all of the associated detector systems. Under current procurement practices this will place the equipment near or at the end of their warrantee periods at the projected CD-4 date.

- The committee drilled down to one of the requirements documents and found the signature requirements in need of an update: missing were members of the newly constituted integration task.

Comments

- We congratulate the Tracker and TDAQ projects for significant progress in preparation for the construction phase. Both projects have done an excellent job in performing the necessary tests, advancing the design and documenting their efforts.

- As a matter of presentation strategy in preparation for a CD-3c review, it would be beneficial to present plans as a baseline technology and an opportunity (listed in the risk registry), instead of a plan with a downstream decision point.

- The QA/QC plan for the tracker is still largely qualitative. It should be made more quantitative. There are situations where it does not make sense to define a specification before testing a number of elements. These should be identified as such now, and quantitative acceptance criteria specified as soon as feasible.

- The scientific effort that is needed to advance the state of the TDAQ trigger algorithms, and more generally to vest the collaboration in their data acquisition systems needs to be identified. There will be a significant ramp up time needed in training these personnel on the design and operation of the TDAQ prior to their full integration with the TDAQ algorithm development effort. These individuals will bring needed scientific expertise to a very technical component of the project and will be able to validate that the system is capable of fulfilling the science needs of the Mu2e experiment.

- The lack of scheduled firmware development effort during the integration and commissioning phases of the project may present difficulties as the actual components are brought together and their integration reveals bugs in or modifications to the firmware that must be performed to permit the system to meet its performance goals. It may be beneficial for the project to specifically schedule a low level of firmware design/modification effort into their deployment and integration plans to mitigate the risks associated with unforeseen changes or needed improvements to the firmware.

- The committee views the appointment of a Trigger Coordinator as a very positive step.

- The 48 hour disk buffer may prove insufficient to insulate the experiment from typical outages and the corresponding support models that are in place and have been observed in the dCache/Enstore storage systems. Increasing this disk buffer would add cost to the project, but would mitigate a known operational risk. This appears to us to be a good candidate to add to the Mu2e risk registry.

- The experiment may want to investigate the possibility of a phased procurement plan for the COTS computing hardware. Such a plan would allow for both early deployment of a TDAQ system with sufficient bandwidth to accommodate the extensive testing and integration of the DAQ with the other detector systems, yet provide for the full scale system to still have a sufficient operational (or warrantee supported) life as the project transitions into operations.

Recommendations

14. The QA/QC documentation for the tracker system should be updated to include quantitative measures of the acceptance criteria for components.

15. The project should work with the collaboration to identify scientific effort for TDAQ development of software and firmware. The risk registry should be updated to incorporate the risk that this effort will not materialize from within the Mu2e collaboration and associated effects on cost and schedule.

3.0 Project Management

3.1 Cost and Schedule

Subcommittee: Bill Freeman, Jeff Reiser, Mohammed Elrafih, Lavada Cartwright (Observer), Brian Smith (Observer)

Charge Questions:

- Are the current Project cost and schedule projections consistent with the approved baseline cost and schedule?

Yes, BAC= $225.560M, EAC= $229.317M, VAC= ($3.758M), 22 months float to T0 CD-4

- Has there been adequate progress on the activities approved at CD-3b?

Yes

- Is the contingency adequate for the risks?

Yes, 36% of ETC

Findings

As of the end of Feb 2016 -

- The Budget at Completion for the Mu2e Project is $225.56M and the EAC is $229.317M. The BAC at Baseline (stated in the PEP) was $220.80M.

- The BAC has increased by $4.76M since CD-2

- The Project is 43% complete (BCWP/BAC)

- The values of current project-level cost and schedule performance metrics are: CPI=0.98, SPI=0.97

- The contingency associated with the bottom-up estimate uncertainty on remaining work is $30.8M. The contingency associated with risk exposure is $5.7M. This leads to a total contingency need of

$36.5M. The total available contingency (TPC-BAC+CV) is $46.6M. This is 36% of the Estimate-to-Complete of $131.0M

- The Mu2e Project is using Primavera P6 as its resource-loaded scheduling tool. Activities in the schedule are organized around a comprehensive, detailed WBS developed down to level 4 or, in a few cases, level 5. Separate P6 files exist for each WBS L2 subproject. There are 7598 tasks and 1189 milestones in the full set of P6 files. Labor and direct M&S dollar resources are assigned to the lowest-level tasks. Predecessor-successor relationships are used to link tasks. Milestones are categorized into various tiers, according to who owns those milestones.

- The Project is using Deltek Cobra as its earned-value analysis and reporting tool. There are 73 control accounts and 360 chargeable task codes in which actual costs are collected. Control accounts are typically associated with WBS L3 elements, or, in a few cases, WBS L4 elements. There are 63 control accounts which are currently active.

- The Project has been doing formal monthly earned-value reporting for more than a year, beginning prior to CD-2. The Project was recently part of an EVMS surveillance review undertaken to validate compliance with the certified FRA EVM system used at Fermilab and it was determined that Mu2e is compliant.

- Variance analyses are being performed monthly for control accounts that exceed specified variance thresholds.

- A formal baseline change control process is in place. Twenty-eight BCRs have been processed. Monthly BCRs are processed by bundling individual change requests submitted by Project personnel.

- About 32% of the estimate-to-complete is currently associated with planning packages. Some of these planning packages simply await the determination of contracted costs before they will be converted into work packages. Others will eventually be broken out into several additional tasks or steps will be defined, once the plans are better understood. The Project looks six months ahead for the presence of planning packages to ensure that they are addressed in a timely manner.

- The critical path for the overall project currently passes through fabrication of the Production Solenoid. The vendor fabrication task for the PS is a single task of approximately 33 month duration. The DS fabrication is a similar long-duration task that is near-critical path.

- At CD-2 the T5 CD-4 completion date was Dec 2020, which provided 24 months of float to the T0 CD-4 completion date of Dec 2022. The current T5 CD-4 completion date is Feb 2021. This indicates that there are now 22 months of float remaining to the T0 CD-4 date, a slippage of 2 months since CD-2.

- According to the subject matter expert, a delay of 4 to 6 months in PS/DS fabrications could result with planned changes in the location of PS/DS solenoid fabrications from the vendor facility in San Diego, CA to a facility in Tupelo, MS. Since this work is on the critical path, a corresponding reduction in float to CD-4 could occur.

- In February 2016, there was a negative BCWS in the current period for conventional construction. This was due to a re-plan for the construction contractor on a firm fixed price contract. The contractor missed a milestone and the project worked with them to develop a realistic recovery schedule. The FPD was informed and authorized the re-baseline to a realistic plan.

- CD-3a approval was in July 2014. The scope is nearly completed. TS and DS conductors have been delivered. PS conductor is being fabricated and is scheduled for delivery in the fall of 2016. Currently this has a few months of float.

- CD-3b was approved in March 2015 for the Detector Hall and TS Coil Modules. The detector hall is approximately 60% complete. It has slipped about 3 weeks within the available 6 months of float. The TS coil module contract was placed in November 2015. The contracted amount was below the original estimated cost, and the delivery schedule is ahead of the original estimate.

- A risk register exists and is a living document with risks being actively managed. There are currently 70 threats and 10 opportunities. Forty-two risks have been retired, and 9 risks have been added since CD-2. Mu2e is currently transitioning to the lab's new web based risk register.

- Acumen Fuse was used by the reviewers to analyze the schedule quality (lags - 1212, leads - 6).

- Project documents include a Milestone and WBS Dictionary.

- The project completed a bottom-up estimate in March, 2016.

Comments

- The Project's cost and schedule performance to date has been good, overall.

- Rate of contingency usage to date is acceptable.

- VARs are completed for control accounts that exceed either yellow or red thresholds even though they are only required to report when a red threshold is triggered. This is a best practice.

- The available funding profile and total funding are adequate, given the planned budget profile, BAC, and remaining contingency.

- The Project's high level of involvement in the recent EVMS certification review contributed to that review's successful outcome.

- The P6 schedule and associated snapshots should only include tasks within the project scope and budget.

- When noting dates in tables or on Gantt charts presented in slides, identify whether the dates are baseline or current forecast dates.

- Some of the descriptions in the milestone dictionary are inconsistent with the milestone names. It would be a good idea to scrub the dictionary and fix them.

- Mu2e is compliant with their Risk Management Plan and are using Primavera Risk Analysis to determine an acceptable cost and schedule risk contingency at 80% confidence level. The project's Risk Management Board meets bi-monthly to add, retire, or revise risks.

- Column F of tab RISK REGISTER in the project's Risk Register spreadsheet (Mitigation Cost) is unclear, as we would have assumed it to be specific assignments of money to mitigate risk. However, it does not point to a set of CRs or tasks, whereas all the other columns are well defined.

- Continue to improve the schedule quality by removing or justifying lags, leads, and constraints.

Recommendations

16. Create a set of P6 Gantt charts for the DOE review showing working-schedule bars and PMB bars, together with tables showing current and baseline durations, dates, and date variances, for incomplete activities and milestones.

17. Develop a plan to replace the single long-duration vendor PS and DS magnet fabrication activities in P6 with shorter-duration, more discrete, tasks and/or steps. These should reflect the scope of work in more detail. This is especially important since these long tasks are currently on or near the critical path.

3.2 ESH&Q

Subcommittee: Jim Floyd, Mike Bonkalski, David Rodgers (observer)

Charge Questions:

- Is ES&H being appropriately addressed for this stage of the project?

Yes

Findings

- ES&H is well integrated into the project, and ESH staffing support appears to be sufficient.
- The safety record of the subcontractor performing the conventional facility construction has been excellent.
- All needed documents (ISM Plan, HAR, NEPA, SVAR, various radiation safety analyses, etc.) are at the appropriate level of completion.
- Concerns from earlier reviews regarding the design of the remote handling system have been addressed. A new, more robust design has been developed.
- Fermilab ES&H has been consulted to provide input on the CRV module fabrication procedures. All procedures have fully integrated ES&H into the documents.

Comments

- Flow-down of ESH requirements to the non-DOE academic collaboration partners is very thorough and is a notable practice.
- The cryogenic-ODH risks have been appropriately analyzed for this stage of the project, and the controls may be fairly complex - with several operational modes spanning several areas. Final designs and reviews, though, are not scheduled until much later in the project.
- The installation process will utilize a long-standing, well understood, but not yet fully documented approach. In the larger context, DOE accelerator community expectations and practices are evolving in this area with progressively more coupling between installation work planning and configuration management (generally, but in particular for credited controls). Practices that were adequate in past projects may not be adequate for upcoming projects.

Recommendations

18. The project should initiate coordination with Cryogenic Safety Subcommittee before the CD-3c OPA IPR to assure that its basic assumptions and strategy are aligned with Laboratory requirements.

19. Well before installation begins, the project should analyze, document and review its installation process in a detailed Project Installation Plan that assures:

    a. Clarity in roles and responsibilities

    b. Proper level of top-down monitoring of status

    c. Proper integration between project, commissioning, and operational phases

    d. Appropriate linkage between the installation work planning and configuration management.

3.3 Management

Subcommittee: Elaine McCluskey, Greg Bock

Charge Questions:

- Are the management structure and resources adequate to deliver the proposed final design within the baselines as defined in the PEP?

Yes, if the resources are available, see comments.

- Is the documentation required by DOE Order 413.3B for CD-3 complete?

Yes.

- Are critical procurements on track?

Yes.

- Have recommendations from previous Independent Project Reviews been adequately addressed?

Yes. One recommendation from the DOE CD-2/3b IPR is still in progress - see Cosmic Ray Veto section.

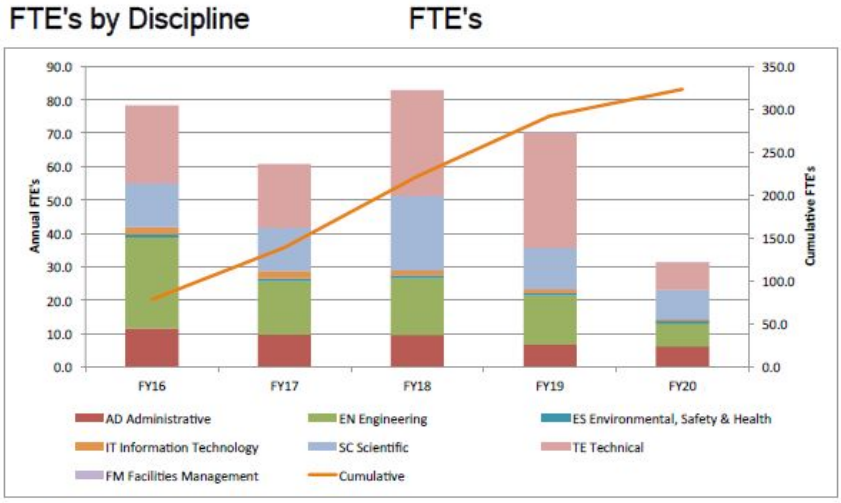
Findings

- The Project is fully staffed with a Project Manager, Deputy PM, full Project Office and Systems Integration teams and eight L2 project teams.

- The Project utilizes four Oversight Committees to advise project management on specific technical and management issues.

- The Project presented a resource profile by discipline and fiscal year as shown below and stated that Fermilab labor agreements with divisions were in place through FY16. Two critical resource issues were identified: 1) need to retain TD & PPD cryo resources to complete design - Project was forced to change to different engineers last year and expressed need to retain what they have now in FY17; 2) designer/drafter resources were stated to be hard to get.

- The Project relies heavily on simulation work from the Collaboration to inform designs. This requires scientific labor both at Fermilab and universities.



Includes Fermi and Non Fermi Labor, costed and uncosted

- The process for procurement planning and execution was presented. Eight critical (>$1M or requiring complex evaluations, or high risk) procurements were identified as yet to be executed, totalling ~$17M. All of these are either executing options in existing contracts, or within the DOE FSO procurement authority. Two are planned to start in FY16, five in FY17 and one in FY19.

- The Project stated that the design is 85% complete overall, using criteria detailed in *Design Completion Definition Document*. The status of design reviews was presented, including a schedule to complete design and hold construction readiness reviews. CRRs are used to validate readiness for procurement and fabrication as well as installation and commissioning.

- The Transition to Operations Plan was presented as a signed document to transition the Mu2e Building later in 2016 from construction to AD and PPD. A plan was presented that identified a Transition to Operations Team that will in the future plan for TTO for the Solenoids in FY19, Detector Subsystems and Beam Delivery in 2020. Additionally, planning for Experimental Operations is also in the planning stage. Budgets have been developed for Operations starting in FY16 through FY22.

- The Project presented a plan for Quality Management with tailored quality and verification tests identified for each subsystem in a QA Spreadsheet. Each subsystem presented information about their approach to quality management. QA processes are already functioning on the Conventional Construction and Conductors.

- The Conventional Construction scope is more than 60% complete, with the heavy concrete construction mainly done, and steel erection, roof decking, and siding underway. Most of the changes to date have been driven by the Project as scope changes due to remote handling revisions or integration coordination. Schedule performance languished in late 2015, but the subcontractor implemented a recovery plan that has brought the project largely back on schedule. This work is not on the critical path and has five months of float to the Solenoids subproject. The EAC is $1.2M less than the BAC at CD-2.

Comments

- The Project team is very strong and has been working well together for several years. The Systems Integration team including new additions over the past year is particularly experienced, and appears to be driving coordination across systems in a timely way. There appears to be a strong working relationship between the Project and Mu2e Science Collaboration leadership.

- The use of Oversight Committees to advise projects is a best practice and the Acquisition Oversight Committee has been particularly effective in this Project.

- Although the Project has been flexible with changes in labor resources over several years, with design completion imminent the Project needs to retain the present team to finish the design. This is particularly true for cryo engineers, but applies to all disciplines. Designer/drafter resources appear to be short in a few areas, and as this resource is critical to completing the designs, any shortages should be understood and addressed quickly. From discussions the Management Subcommittee had with AD, TD, and PPD management during this review, staffing concerns arising from issues such as staff retirements may make this challenging.

- Simulation work does not appear to always be completed early enough to have impact on the design. The Collaboration should focus on simulations that are relevant to the design.

- Procurement is well managed, using a matrixed Procurement Manager and significant project managerial and technical involvement to monitor critical procurements. Generally the upcoming critical procurements are well-planned and appear to be on track; however, at least one (HRS) did not appear to have scheduled activities for procurement planning.

- It was not easily determined how many final design reviews remain outstanding on the project and, in a comprehensive manner, what is the plan to complete the design for each subsystem (e.g., what design choices remain and work remaining until Construction Readiness Reviews). The Project should consider preparing a Final Design Plan that would pull all the information into one location for a better picture of the work and approval processes remaining until construction.

- The Project team and Fermilab management were very responsive to requests for information during the review.

- The Transition to Operations Plan for the building is very advanced and an excellent tool. The Project and Collaboration are commended for assembling an early Transition to Operations Team, led by the Collaboration Co-Spokesperson, that have already identified needed operations budgets. The Project, Collaboration, and Fermilab should work together to ensure that these budgets are incorporated into laboratory budget planning for future years.

- The QA/QC planning is well along in concert with the maturity of the design and pre-procurement planning, with a few exceptions as noted in the other subcommittees.

- The Conventional Construction is being well managed by FESS with close attention to schedule. The Systems Integration Team works closely with the Conventional Construction L2 Manager to

ensure the completed facility will meet project needs. This will likely result in less rework of some installed utilities as the Detector subsystems better understand experimental layouts.

Recommendations

20. Before the DOE CD-3c IPR, the Project should meet with AD, PPD, and TD to get statements from the divisions regarding commitment to labor resources for FY17 - FY20, particularly in the face of several impending senior engineering retirements.

21. Given that Mu2e Project is going into a 4-year construction period, the Directorate should work with the Project to ensure adequate access to required resources to complete the Project.

22. Proceed to the CD-3c DOE OPA IPR.

4.0 Appendices

A. Charge

B. Agenda

C. Review Committee Contact List and Writing Assignments

Appendix A

Charge

Director's CD-3c Review of Mu2e

April 19-21, 2016

Memorandum

22-Mar-2016

To: Mike Lindgren, Chief Project Officer

From: Nigel Lockyer, Director

Subject: Director's CD-3c Review of the Mu2e Project

Please organize and conduct a Director's Review of Mu2e on April 19-21, 2016 to assess the project's readiness for the DOE CD-3c review and approval process. On July 10, 2014, DOE approved CD-3a to allow procurement of superconducting cable for the Mu2e solenoids. On March 4, 2015, DOE approved CD-3b to allow construction of the Mu2e Detector Hall and procurement of the Transport Solenoid Modules. CD-3c will approve fabrication/procurement of the remaining baseline scope. The Project is scheduled for a DOE CD-3c review on June 14-16, 2016.

The Mu2e Project will construct a new facility to enable the world's most sensitive search for charged lepton flavor violation by searching for the conversion of a muon to an electron in the field of a nucleus. Mu2e will be ~10,000 times more sensitive than the world's current best limit. The Project consists of modifications to the existing Fermilab accelerator complex, construction of a new external beamline, construction of a new detector hall on the Fermilab site and construction of a new detector to search for muon conversion. The detector includes a complex system of superconducting solenoids, a collimation and charge selection system for producing the world's most intense low-energy muon beam, a low-mass tracking detector operating in vacuum, a crystal calorimeter and a cosmic ray veto.

The review committee should respond to the following questions:

1. **Design and Scope.** Is the design sufficiently mature so that the project can continue with procurement, fabrication, and construction? For those elements of the design that are still not finalized, has the project shown that there are no major issues that need to

be addressed and that they are on a clear path to a final design? Have recommendations from prior independent design reviews been adequately addressed?

2. **Cost and Schedule.** Are the current Project cost and schedule projections consistent with the approved baseline cost and schedule? Has there been adequate progress on the activities approved at CD-3b? Is the contingency adequate for the risks?
3. **Management.** Are the management structure and resources adequate to deliver the proposed final design within the baselines as defined in the PEP? Is the documentation required by DOE Order 413.3B for CD-3 complete? Are critical procurements on track? Have recommendations from previous Independent Project Reviews been adequately addressed?
4. **Environment, Safety, and Health.** Is ES&H being appropriately addressed for this stage of the project?

The committee is asked to present a draft of their report at the review closeout and to issue the final report within two weeks of the review's conclusion.

Nigel Lockyer
Director of Fermilab

Appendix B

Agenda

Director's CD-3c Review of Mu2e

April 19-21, 2015

ReadyTalk Information for Plenaries and Closeout Session:
Toll-Free Dial-In: 866-740-1260; Access Code: 5571684#

Tuesday April 19

EXECUTIVE SESSION – Comitium (WH2SE)

8:00 – 8:50	AM	50	Executive Session	Greg Bock

PLENARY SESSION – One West (WH1W)

9:00 – 9:10	AM	10	Welcome	Tim Meyer
9:10 – 10:10	AM	60	Project Overview	Ron Ray
10:10 – 10:40	AM	30	Accelerator	Steve Werkema
10:40 – 11:00	**AM**	**20**	**BREAK (Outside One West)**	
11:00 – 11:30	AM	30	Solenoids	Mike Lamm
11:30 – 12:00	AM	30	Muon Beamline	George Ginther
12:00 – 12:20	PM	20	Tracker	Aseet Mukerjee
12:20 – 1:20	**PM**	**60**	**LUNCH (2nd Floor Crossover)**	

PLENARY SESSION – One West (WH1W)

1:20 – 1:40	PM	20	Calorimeter	Stefano Miscetti
1:40 – 2:00	PM	20	Cosmic Ray Veto	Craig Dukes
2:00 – 2:20	PM	20	Trigger and DAQ	Ryan Rivera
2:20 – 2:50	PM	30	Integration	Karen Byrum
2:50 – 3:15	**PM**	**25**	**BREAK (Outside Comitium)**	

PARALLEL BREAKOUT SESSIONS

3:15 – 5:00 PM 105

Session 1: Management – Comitium (WH2SE)
Session 2: Accelerator – One West (WH1W)
Session 3: Solenoids – Curia II (WH2SW)
Session 4: Muon Beamline – Directors' (WH2E)
Session 5: Calorimeter/Cosmic Ray Veto – One East (WH1E)
Session 6: Tracker/DAQ– Black Hole (WH2NW)

5:00 – 6:30 PM 90 Full Committee Executive Session – Comitium (WH2SE)

Wednesday April 20

PARALLEL BREAKOUT SESSIONS

8:00 – 10:00	AM	120	Continued in same rooms
10:00 – 10:20	**AM**	**20**	**BREAK (Outside Comitium)**

PARALLEL BREAKOUT SESSIONS

10:20 – 12:00	AM	100	Continued in same rooms
12:00 – 1:00	**PM**	**60**	**LUNCH (2nd Floor Crossover)**
1:00 – 2:00	PM	60	Response to reviewer questions – Comitium (WH2SE)
2:00 – 3:30	PM	120	Subcommittee Executive Session/Report Writing – **in Breakout Rooms**
3:30 – 6:00	PM	120	Full Committee Executive Session – Comitium (WH2SE)

Thursday April 21

8:00 – 10:45	AM	165	Committee Report Writing– Comitium (WH2SE)
10:45 – 11:30	**AM**	**45**	**BREAK (Outside Comitium)**
11:30 – 3:30	PM	120	Full Committee Executive Session Dry Run with Working Lunch – Comitium (WH2SE)
3:30 – 4:30	PM	60	Closeout Presentation – One West (WH1W)
4:30	PM		Adjourn

Appendix C

Review Committee Contact List and Writing Assignments

Director's CD-3c Review of Mu2e

April 19-21, 2016

Chairperson

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Project Management

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Muon Beamline

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*Lead

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