Fermilab

Closeout Presentation

Director's Independent Design and CD-2/3 Review of the Mu2e Project

July 8-10, 2014

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Executive Summary

The Mu2e Project ("the Project") is being constructed at Fermilab to support a compelling discovery experiment with sensitivity to a broad range of new physics. Mu2e is a search for Charged Lepton Flavor Violation (CLFV) via the coherent conversion of $\mu^- N \rightarrow e^- N$ and is a high precision experiment with a factor of 10,000 more sensitivity than existing measurements. It is an integral part of the overall muon program at Fermilab and the US HEP program as described in the recent P5 report. Mu2e relies on the completion of several Accelerator Improvement Projects (AIPs) to transport and deliver the beam and shares part of the delivery line with the g-2 experiment. The Mu2e Collaboration currently has approximately 145 collaborators from 28 institutions. The Project benefits from significant in-kind contribution by INFN for part of the calorimeter and for help with the solenoids.

There has been significant progress since the Project received CD-1 in July 2012 and many down selects have been made to help establish a more final design. The estimated degree of project definition is 56%. The Project has a cost estimate based on a resource loaded schedule (RLS) implemented in Primavera with over 6,000 activities and documented through a set of Basis of Estimates (BOEs). The RLS is integrated with Cobra and the Project has started exercising earned value management system (EVMS) tools in a preliminary manner. The critical path is through the Detector Solenoid (DS) however, the other superconducting solenoids (PS and TS) are both near critical path.

The Total Project Cost (TPC) is $271M with a current Estimate to Complete (ETC) of $172M and a percentage contingency on ETC of 31%. The contingency analysis incorporates both estimate uncertainties and risk-based contingency. The Review Committee has concerns that the TPC including risk-based contingencies will increase as additional design work is performed, large procurement contracts are enacted, and estimates are updated. The level of this concern is on the order of $5M to $10M.

The schedule shows the Key performance Parameters will be satisfied by the 1st Quarter FY21. This baseline completion date provides two years of float to the 1st Quarter of FY23 CD-4 date. However, there is significant off project work after the KPPs are met involving final installation of the detector and shielding. This agreement was established in conjunction with the DOE and the Laboratory to accommodate precision solenoid field mapping.

It is troublesome that the Project does not yet have an approved funding profile from the DOE. This significantly hampers the ability of the Project Office to present a fully consistent resource loaded schedule.

The Review Committee notes that the difference between the "Threshold" and "Objective" Project Key Performance Parameters (KPPs) represents a level of scope contingency but that the estimated cost difference is not significant. The Review Committee believes the Mu2e management team is capable of successfully executing the Project.

The Committee reviewed the technical design of the nine major technical systems (Accelerator, Conventional Construction, Solenoids, Muon Beamline, Calorimeter, Cosmic Ray Veto, Tracker, Trigger and DAQ). It is the assessment of the Review Committee that the designs presented will meet the CD-2 design requirements and that the Conventional Construction can be ready for CD-3. Most systems are well past the preliminary design level and many are engaged in various stages of final design.

The Review Committee believes that the Project should be ready to proceed to the DOE CD-2 review in August 2014 and that the Conventional Construction section will be ready for a DOE CD-3 review following consideration of the recommendations contained in this report.

1.0 Introduction

A Director's Independent Design and CD-2/3 Review of the Mu2e Project was held on July 8-10, 2014 at the Fermi National Accelerator Laboratory. The objects of this review was to assess the level of maturity of the Project's design and to determine if the project meets the Critical Decision (CD) 2/3 (CD-2, Approval of Performance Baseline and CD-3, Approve to Start Construction) requirements as specified in DOE O 413.3B. To meet the design requirements for CD-2 the design has to be at the preliminary level or greater, and for CD-3 the design has to be at the level of final or near final design.

Additionally, the committee assessed the Project's progress on addressing the recommendations from the prior reviews: DOE CD-3a conducted June 10, 2014; three DOE Mini-Review teleconferences on September 26, 2013, April 9, 2013, and November 19, 2012; DOE CD-1 Review conducted on June 5-7, 2012; Director's CD-1 Review was held on April 3-5, 2013; and the Director's Conceptual Design Review conducted on May 3-5, 2011. The charge included a list of specific questions to be addressed as part of the review. The assessment of the Review Committee is documented in the body of this closeout presentation.

This closeout report is broken down into two basic sections. The first section provides the assessments of the project's design of technical deliverables and project management. Each area within this first section is generally organized by Findings, Comments and Recommendations. Findings are statements of fact that summarize noteworthy information presented during the review. The Comments are judgment statements about the facts presented during the review and are based on reviewers' experience and expertise. The comments are to be evaluated by the project team and actions taken as deemed appropriate. Recommendations are statements of actions that should be addressed by the project team. The second section of this presentation has the committee's answers to the review charge questions.

The Mu2e Project is to develop a response to the review recommendations and present it to the Laboratory Management and regularly report on the progress during the Project's Project Management Group Meetings (PMGs) and at the Performance Oversight Group (POG). The recommendations will be tracked to closure, in the iTrack system. Documented status of the project's resolution of the recommendations will need to be available for future reviews.

2.0 Technical

2.1 Accelerator

Lead: Paul Derwent

Contributors: Keith Gollwitzer, Jim Hylen, Vaia Papadimitriou

Findings

- 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 Accelerator provides 8 kW, 8 GeV beam through resonant extraction to the production target. There are 8 transfers from the Recycler in a 1.33 second cycle. 1e12 beam is slow extracted over 54 msec.

- The proton pulse is required to have a 1695 nsec spacing with a maximum width of 230 nsec. The out of time extinction (relative intensity outside the pulse window) is required to be 10^{-10}.

- The production target is installed inside the production solenoid. Design requirement is > 1 year lifetime.

- Resonant extraction will use the 3rd order resonance, driven by harmonic quads and sextupoles. Spill intensity is regulated by an RF knockout technique, with <50% turn to turn variation.

- Network connections for the Mu2e building (Ethernet, FIRUS, phone, etc.) are provided through this WBS element.

- Extensive modeling of radiation due to beam losses has been done. With supplemental shielding and a Total Loss Monitor (TLM) system of interlocked detectors, the proposed system prevents unacceptable external radiation dose rates. The modeling uses a 1.25% beam loss at the extraction septum and 0.3% distributed beam loss around the enclosure. There are changes to the access to the AP30 service building due to the calculated radiation dose rate. Calculations of the exposure at Wilson Hall show that the expected dose rate is <1 mRem/year.

- The new M4 beam line has been designed in conjunction with the M5 beam line for muon g-2. The beginning of the M4 beam line is shared and will be installed by the muon g-2 project. For Mu2e, the beginning of the common beam line needs two changes: the muon g-2 extraction kickers are replaced by the Mu2e extraction septa and changing the tilt of the vertical dipole where the beam line splits into the individual M4 and M5 beam lines.

- The un-common part of the M4 beam line has several sections with different functions: horizontal bend, extinction, final focus and matching sections. The extinction section optics is undergoing modification (location and purpose of collimators). This change is not documented in the TDR. In addition, the TDR description of the extinction system does not match the current planned system (difference of using two or three harmonics for the AC dipoles) which is reflected in the BOEs. The modifications are in response to simulations studies and will improve the effectiveness of the extinction system.

- Most of the M4 beam line magnets are expected to be re-purposed magnets mainly from the Antiproton Source Accumulator. The plan is that these magnets are to be moved from the Accumulator directly into position prior to g-2 operation without testing/refurbishment. Other magnets from storage will be refurbished and there will also be construction of magnets of an existing design. It is not clear whether there are power supplies available to be re-purposed.

- Instrumentation devices for the M4 beam line have been designed and planned as part of the integrated Muon Campus needs. The designs are based upon current Fermilab beam instrumentation. The Mu2e schedule has the construction of the instrumentation and controls after the Muon Campus AIPs and muon g-2 projects have finished.

- The target design is well advanced, however there is a low risk that the target could corrode in less than the desired 1 year lifetime. The target is radiatively cooled, which provides significantly simpler remote handling during change-out and eliminates risk of coolant leakage, but the resultant high temperature may lead to rapid corrosion at the currently specified vacuum level. Testing is underway to confirm target survivability, along with investigation of possible coatings as mitigation if needed. If the radiatively cooled target proves unworkable, the fall-back is a water or He cooled target. Such a target has no technical showstoppers, but with the extra complications, remote handling costs would increase by an estimate $3.3 M.

- The extinction system is getting close to a mature design, with the AC magnet system presented as working well for Gaussian beam, but the upstream collimation system to eliminate long transverse tails is yet to be designed. This upstream collimation will have some impact on the magnet layout, although this is not expected to impact the civil design.

- The primary proton beam dump and Production Solenoid Heat and Radiation Shield (HRS) are not repairable in case of failure because of residual radioactivation. They must last for the lifetime of the experiment.

- The project team described a BOE/P6 review process to vet the information in both cost and schedule. They identified several areas where they have uncovered discrepancies between the information in the BOE documents and the P6 schedule and described a process underway to update the information.

- Three WBS L3 sections are requesting CD-3 at this time: 475.02.03 Instrumentation and Controls, 475.02.04 Radiation Safety Improvements, and 475.02.06 Delivery Ring RF Systems.

- For each part of the Accelerator sub-projects, an installation schedule was presented. The overall schedule has several unrealistic dates for installation of certain components (during muon g-2 operation or before the beam line enclosure is complete). There is no overall installation plan which avoids possible interferences between Accelerator sub-projects with each other as well as with other Muon Campus activities.

- To meet one of the Accelerator Objective KPPs, beam (not necessarily resonantly extracted) needs to be delivered to the diagnostic absorber. This activity does not exist in the schedule. The plan is to deliver 1-turn beam (low beam power) to the diagnostic absorber using the muon g-2 extraction kickers (prior to replacement by the Mu2e extraction septa). However, the M4 radiation safety system is not scheduled to be installed until half a year after the septa installation. This scheduling is inconsistent and incomplete.

Comments

- The Radiation Safety L3 Manager has retired the risk on the TLM (Accel-020 'TLMs cannot be used to limit the intensity and duration of beam loss') without final approval from the laboratory ESH&Q section. We believe that while the probability of this risk being realized is low, it is premature to retire this risk.

- Studies are being pursued of design changes that would relocate the Remote Handling Room from beside the Target Hall to above the Target Hall. Top loading remote handling looks attractive if the fallback option of a water or He cooled target is required. Although the Civil bid package contains the option to remove the side-located Remote Handling Room, it does not contain a well-defined way to add the top-located Remote Handling Room, so exercising this option would involve re-negotiation of the Civil contract along with re-design and some delay. Other than this, the technical design appears far enough along to support CD-3 for Civil construction.

- In the costed design, essentially the only monitoring of the production target is the external extinction monitor. While this appears adequate to catch changes during operation, having some kind of detector such as a profile monitor between the target and the dump during beam-to-target alignment scans and while trying to confirm the beam spot size and shape on target would provide significantly more information and in an easier to understand format. This monitor could be removed during normal operation to reduce radiation damage to the monitor.

- Although not presented by the project, there has apparently been discussion of possible later upgrades to the Mu2e beam power. The HRS and dump are designed for 8 kW of beam, they will be highly radioactivated during Mu2e operation. Unless features are designed in now to allow later replacement, it seems unlikely that upgrading later for higher beam power would be possible.

- The interfaces and responsibilities between the Muon Campus projects, the g-2 project, and the Mu2e project were discussed in the plenary and breakout sessions. The details presented in the TDR were not always clear. The documentation and presentations at the DOE review could use some clean up to make it clear to the reviewers.

- The loss modeling and radiation dose calculations work under the assumption of a 1.25% beam loss at the extraction region. With 3 feet of additional steel shielding in the tunnel, the dose rates in the AP30 service building are calculated to be ~40 mRem/hour at normal operating intensity and losses, making the building (and part of the parking lot) a radiation area, requiring rigid barriers with locked gates. Larger losses at the extraction region would increase the dose in the service building. Activation calculations in the region show that there will be a need for detailed ALARA plans for any maintenance activities.

- The design of the upstream part of the M4 beam line common with muon g-2 has been appropriately designed so that in either mode this section of beam line is part of a vertical achromat. A single vertical dipole will have to be tilted between modes.

- The Mu2e-specific part of the M4 beam line will contain sections that will perform the functions needed to provide the specified beam. The on-going modification of the extinction optics will improve the beam quality.

- Re-purposing magnets saves the project money. In the case of magnets coming from storage, the project is doing a refurbishment. For the Accumulator magnets, there is no refurbishment or test planned before installation. There is no scheduled activity to repair any of the magnets which do not work after being moved and no associated risk in the risk registry.

- The common instrumentation and controls needed for the Muon Campus results in lower overall costs to all projects and AIPs involved. However, since the Mu2e schedule has construction of instrumentation occurring after the others have been finished, Mu2e will likely incur a higher cost than if all Muon Campus devices are assembled at the same time.

- Installation of the M4 beam line involves coordination with the muon g-2 project and Fermilab operations. The off-project milestones are only the beneficial occupancy of the Muon Campus enclosure GPP and the muon g-2 run period. Between the end of the GPP and the start of muon g-2 operations, both Mu2e and muon g-2 projects will want to install the beam lines in the new enclosure. There should be coordination between the two projects.

- Project assumptions document has not been signed by the Accelerator Division. Availability of equipment and what scope and risk have been transferred to the AD responsibilities have not been accepted. This lack of agreement may put the project at risk.

Recommendations

1. Consider the addition of a monitor placed between the production target and the dump for use in target scans and special tests to understand the beam optics at the target.

2. Consider doing an analysis of cost/contingency/risk of failure in repurposed Accumulator magnets in the M4 line.

3. Update the TDR and appropriate BOEs to reflect the changes to the M4 optics of the extinction section as well as the changes in the extinction system.

4. Investigate cost savings if assembly of all common Muon Campus instrumentation can occur at the same time.

5. Review the schedule to make sure installation does not interfere, or overload shared resources, within the project and with other Muon Campus activities.

6. Create activities and milestones that cover the delivery of beam to the diagnostic absorber and review schedule logic to achieve Accelerator Objective KPP.

7. Assign a dedicated mechanical engineer to serve as systems or integration engineer for the Target Station. This engineer should help develop and review component and system requirements, oversee work in the different areas, and assure proper integration of all components and systems. We recommend identifying an individual by the CD-2 review.

8. Correct the P6 schedule prior to the CD-2 DOE review.

2.2 Conventional Construction

Lead: John Busch

Contributor: Tracy Lundin

Findings

- The Mu2e project has issued RFP's (construction contract documents) for construction contractors to submit bids on by July 23, 2014. Two sets of documents have been issued: one for the Mu2e detector hall and one for the MC beamline enclosure. The former scope is seeking CD2/CD3 approval and the latter is being executed as a GPP project and does not require CD approval. Bidders will submit one bid that includes both scopes of work.

- The selection criteria for the Mu2e detector hall was stated to be based 40% on price and 60% of yet-to-be defined criteria.

- The Mu2e construction contract documents scope includes a remote handling room located at the lower detector hall elevation. Bids are sought for this scope with a "deduct option #1" to omit this room. The deduct amount will be a non-binding value. Addendum A dated February 17, 2014 states that the decision of whether or not to exercise this option will be made within 45 days on contract award which is scheduled to be in January 2015. If this deduct option is exercised Conventional Construction (CC) must go back to the AE (Architect-Engineer) design firm to revise the design and contract documents accordingly causing a delay of several months. Once available, the revised design will be issued with a request for cost proposal that construction contractor will price and submit with a revised bid. A contractual supplemental agreement will then be executed. The CC scope is being executed several years before the user will fully occupy the space. This is being done to take advantage of current favorable construction industry economic conditions.

- The project risk register includes only two CC risks; one threat and one opportunity both related to the value of construction bids to be received on July 23, 2014. Additional CC risks are included in the L2 risk register.

- A laboratory wide comment and compliance review, by Fermilab staff both internal and external to the project, was conducted on the 90% final design of the Mu2e detector hall that is out for bid. Aon, Inc. (a consultant) did an independent review of the final design of fire & life safety aspects of the project.

- Page 7 of 25 of Exhibit A, dated February 2013 includes the "requirements, responsibilities, and expectations" of construction contractor staff. A Project Manager is not included in this list of contractor's staff.

- A Project Execution Plan has been produced for the Project. CC has contributed to the Plan.

- The AE was contracted to produce 30/60/90/100% construction contract documents. The 30% documents (drawings and specifications) are considered to be equivalent to Preliminary Design. The project has produced a Technical Design Report (TDR) which incorporates overview write-ups and sample drawings from CC.

- The AE has produced a cost estimate at the 30/60/90% levels. FESS has reviewed the estimates and has made some modifications. An Independent Cost Estimate (ICE) for the project is underway, but has not been completed.

- A NEPA Categorical Exclusion was obtained.

- A muon campus SWPPP permit was obtained to cover MC-1, Mu2e, and MC Beamline. A soil erosion control plan has been developed.

- A Domestic Water Permit to Construct has been obtained. IEPA Sanitary Sewer Permit is not required.

- Utility requirements are well documented and have been communicated and coordinated between the scientific technical teams and CC.

- Radiation design considerations have been incorporated into the design of the water and HVAC Systems.

- A project level Hazard Analysis Report has been performed and CC has contributed to the report. Excavation hazards, personal protection equipment (PPE), Arc Flash, Lock-out Tag-out (LOTO), etc., were included.

- Project Quality Assurance is following the Fermilab QA Program. Design QA is outlined in the FESS AE Handbook. The AE's office in Cleveland performed an independent QA review of the design documents. Construction QC is given in the technical specifications, and Construction QA is given in Exhibit A.

- LEED Certification is not being pursued. Guiding principles of High Performance Sustainable Buildings is being followed.

- The CC requirements, dated June 13, 2014, say, "enterprise and organizational requirements, referenced in the CDR, Chapter 6, are incorporated into the building design."

- The CC organization chart shows multiple boxes that all have the same name listed as being the responsible party. This does not reflect that fact that the boxes are time phased and that some responsibilities are shared with the A/E. The CC L2 manager believes that he has adequate support.

- The construction cost estimate is a contractor style estimate that is developed by assembling crews and equipment needed for each task and the time for the crew to accomplish the task. The cost estimate was developed by the same firm that designed and estimated the recently bid Fermilab MC-1 building that allowed calibration of estimate methodologies.

- A preliminary ODH analysis has been completed that has resulted in the CC enclosures being designated as Class 0 which influences the ventilation system requirements. A final ODH analysis will be completed when a design of the cryogenic system is available. The final analysis may, or may not, result is changes to the ventilation system.

- Except for one, all recommendations from prior reviews have been closed out. The one remaining to be closed out is from the 2011 Independent Design Review.

Comments

- Given the close proximity to each other executing both construction packages as one construction contract by one contractor is a good approach.

- The CC for construction of the detector hall is out to bid. A cursory review of the documents indicates that the drawings and specifications are at satisfactory completion level for the bidding.

- Fermilab personnel both internal and external to the project performed project reviews at 30/60/90% submittals. It is not clear that the lab-wide comment & compliance review, the Aon review of life safety systems, and the FESS staff review are sufficient to meet the CD-3 requirement of conducting a final design review by a team external to the project.

- Because the CC scope is moving into construction and other parts of the project are only at the CD-2 stage, it appears that there are opportunities for the development of technical systems scope to potentially impact CC. Discussions with the Mu2e risk manager indicated that risk registers did not include a risk (either retired or active) for the possibility of technical system changes to drive changes in the CC scope.

- The combination of the TDR and the 30% Drawings and Specifications is considered to satisfactorily meet the needs of Preliminary Design.

- A thorough Value Engineering exercise was performed, and it appears that prudent choices were made for the items to be incorporated into the design.

- Permitting requirements – NEPA, SWPPP, Water Permit to Construct – have been met.

- Some mitigation efforts were made to reduce the impact of the high magnetic fields; however, since there is not much experience with building components within the range of high magnetic fields, there is still a risk. This risk can be mitigated by performing a secondary commissioning of the building systems after the magnets are commissioned and process utilities are at full use.

- Overall contingency for CC is 17% ($3.18M). There are several items that are not presently budgeted which will reduce the contingency. E&O's (Errors and Omissions), unforeseen site conditions, and owner requested changes will likely consume part of this contingency. Including the new "Changing Technical Requirements" risk will also likely consume part of this contingency. However, the overall contingency for the CC appears adequate.

- The summary report for Mu2e High Performance Sustainable Buildings (HPSB) was reviewed and appears that the guiding principles were followed. Due to the highly technical nature of the building, significant process loads, and the presence of radiation, a prudent approach towards sustainability is recommended. It appears that this has been done.

- While the CC requirements are dated June 2014, the statement that "enterprise and organizational requirements, referenced in the CDR, Chapter 6, are incorporated into the building design" suggests that requirements may not have been completely updated since the CDR.

- Although Mu2e is complicated for its size, Fermilab and the AE have experience estimating costs for similar facilities. There is recent experience from the MC-1 building. The construction cost estimate and schedule appear adequate and acceptable.

Recommendations

9. Address the CC "deduct option #1" and the process for exercising the option in the plenary session of future reviews.

10. Add a project level risk to the risk register regarding the possibility of technical system changes, including but not limited to exercising deduct option #1, causing changes to the CC scope/cost/schedule. Assess the magnitude and probability of this risk with respect the "savings lost" by delaying award of the CC construction contract. The risk value should be reviewed periodically.

11. An Independent Cost Estimate (ICE) should be performed.

12. Perform a secondary commissioning of the MEP systems after scientific technical components are installed and commissioned.

13. Develop the selection criteria for selecting the Mu2e detector hall construction contractor.

14. Add the requirement to Exhibit A for contractor to have a dedicated Project Manager – not necessarily full time.

15. Recommend advancement for CD-2/3 DOE review contingent upon addressing all recommendations.

2.3 Solenoids

Lead: Shailendra Chouhan

Contributors: Bob Kephart, Al Zeller

Findings

- The solenoids are the major cost element and define the critical path for the project.
- The detailed superconducting solenoid magnet design (PS, TS and DS) were presented and all the key issues such as magnetostatic calculations, quench protection, power supply and except detailed mechanical designs were covered.
- Magnetostatic analyses were performed including errors from fabrication, assembly, and alignment tolerances. Field data/ results were provided to accelerator group for optics calculation.
- The Production Solenoid (PS) is designed for 4.6 T design and field uniformity requirement +/-5%, Iop Margin ~ 30 % are understood and documented. The Transport Solenoid (TS) requirement is Bmax= 2.5 T. Both magnets are designed to have linearly decreasing axial fields. The number of stopped muons depends linearly on the achieved PS and TS maximum fields allowing significant performance margins.
- To support the physics goals of the experiment, the Detector Solenoid (DS) requirement is Bmax= 1.0T in the region of the detector with a field margin of ~ 5% nevertheless this magnet also has large current and temperature margin.
- A design detail of all the solenoids has been captured in the Mu2e Technical Design Report (TDR).
- Active quench protection system (QPS) will be used to protect all the solenoids. There is strong coupling and magnetic forces (100-130 Tons) between PS, TS and DS. In the event of the quench in any one the others would likely be discharged at the same time. Failure mode analysis for the QPS has been performed and was presented.
- Conductor design for all three solenoids is in an advanced stage and conductor has been ordered. At least one extra length is planned for TS coils to replace a coil which might fail its acceptance test. There is one extra length for both PS and DS to replace one small coil segment should it fail acceptance tests. However, if either of the largest two segments of PS failed they would have to order new conductor with at least a one year delay.

- The senior personnel in the solenoid group are experienced SC magnet designers and builders with years of experience with magnets built in house. The team does not have experience with managing big SC magnets built in industry.

- A "design and build" bid was released for PS and DS. There was a positive response from several qualified companies and the committee was informed that the project is close to awarding a contract to an industrial vendor with Fermilab providing the conductor.

- The plan is to assemble TS in house at Fermilab using completed coils and other cryostat components built in industry. Early test on the vacuum pressure impregnated coils such as hi-pot, electrical at low current, turn-to-turn short, cold shock, etc. will be performed at the vendor's site. Full field cryogenic tests as a complete module will be done at Fermilab.

- There are only two risks in the project registry that impact cost: SOL-157 (PS conductor does not meet specs) and SOL-066 (late delivery of solenoid).

- Existing power supplies of TeV Low Beta Quad systems and TEL Solenoid will be reused as these supplies satisfies and meet specifications. Trim power supplies and dump resistors will be new.

- An Acquisition Oversight Committee (AOC) with external SC magnet experts has provided advice to the mu2e magnet team in the past. This committee met twice to discuss solenoid procurement most recently about 6 months ago.

Comments

- Potential issues exist with Technical Division labor since LCLS-II, LHC magnets, PIP-II, CLAS-12, Mu2e, and smaller projects all compete for a fixed pool of human resources. Success will require adequate labor to support both TS construction and PS/DS oversight at the vendor. The team must also prepare for and carry out the required magnet test program as well as design and build the cryo distribution system. The Project will need pre-emptive vs reactive mechanisms to secure needed labor.

- From the standpoint of managing risks, having all solenoids rollup up in one project risk is not very useful. The risks associated with in-house fabrication of TS are very different from those associated with fabrication of PS and DS in industry

- Given the complexity of the planned SC magnets for mu2e, it is not plausible that the technical, cost, and schedule risk for the solenoids are all "low" as was stated in the presentations. The committee was not presented with sufficient information to judge the risks nor the required contingency. The magnet group needs to create a risk matrix including the many unlikely but expensive failure modes that they might encounter in creating 66 unique superconducting coils to establish defensible risk assertions, contingencies, and mitigation plans.

- There are cost risks that are not simply schedule delays. If a coil needs to be re-potted, re-wound, replaced, etc., there should be technical, cost, AND schedule risk(s) associated with such events. SC magnet failures are dominated by "unanticipated" faults, sometimes with costs and long recovery times. While one can mitigate these to reduce the probability, one cannot eliminate such risks. The committee was not convinced that SC solenoid risks are adequately captured in the project Risk Register or that the contingency assigned to the magnet project is adequate and risk based.

- The rational for the 18% contingency assigned to the PS and DS solenoids was not obvious. It should not be established at this value simply because they have vendor bids. Such complex "fixed price" contracts often grow in cost.

- Ideally risks should be rolled up into the solenoid risks in the overall project risk register with required contingency amounts assigned. The magnet team told us that solenoid risks in the project risk register and associated dollar amounts were " given to them" by the project manager (Ron) instead of doing their own evaluation of the risks and potential cost and schedule exposure leading us to question their ownership of the contingency assigned to their subproject.

- The lack of sufficient conductor to allow winding of a complete replacement coil for every solenoid is in need of more thought. While QA and significant vendor oversight goes a long way to insuring there aren't any useless coils, even the most diligent oversight may fail. Consideration should be given to increasing the conductor order to mitigate risks. One should also take extraordinary oversight measures when the bigger coils are being wound to better ensure that no problems occur.

- During drill-down, the CAM was very proficient in the technical details. The cost, schedule and EVMS responses were not quite as good. Effort should be made to bring these areas up to the same level. For example, it should be possible to locate the forms and instructions for VARs without having to follow up the management chain.

- It should be stated explicitly in talks that integration and assembly is handled by one engineer, so that interfaces get taken care of.

- The Committee asked about the principal technical, cost, schedule risks for the SC magnets but the magnet team did not have a table or document that captured these risks with probabilities and cost impacts. In some cases they had thought through some ways to minimize risks, but these were not presented or described succinctly.

- Although they have a magnet advisory committee, they should talk to other groups involved in recent SC magnet procurements (e.g. JLAB, U.S. ITER) to identify possible risks and pitfalls with management of industrial procurements.
- The nature of the PS/DS solenoid contracts is that they are a hybrid of a "Build to design/print" and a build to "specification" beyond the "design" the exact definition of what they were buying with this contract seemed not well thought through.
- The team sees it as a fixed price contract and has assumed 18% contingency
    - The Committee sees no basis for this contingency estimate
    - The magnet team should examine contingency use experience from other "fixed price" SC magnet contracts. (e.g. JLAB, or PNNL, or LHC detector magnets)
    - The magnet team should use the risk register to estimate contingency required and to establish mitigation plans
    - The magnet team had no written plan to "manage" these big contracts, nor were they able to verbalize their strategy or the tools that they intended to employ. In particular the committee believes they will need:
        - Contract measures that include incentives/penalties to maintain the schedule
        - A person imbedded at the vendor's plant during key fabrication steps
        - An agreed upon change process with agreed upon labor rates for changes
        - A technical and/or cost dispute resolution process
        - A QA plan owned by the FNAL magnet team in addition to whatever QA plan is put in place by the vendor.
        - Provisions in the contract for the case in which a coil is damaged or fails acceptance tests such that it has to be replaced. This provision should specify which party pays for the new conductor under various circumstances and what steps will be taken to maintain or recover schedule and at whose expense.
        - Provisions connecting ultimate success or failure of the magnet to financial payments to the vendor
- PS Solenoid: Coil packs are cooled externally by high purity Al strips. Beam heating is estimated to produce a 0.3 K temperature rise in the middle of the PS coil. However this is with some assumptions about the thermal conductivity of layers of insulation. Make measurements to validate the model.

- PS radiation shield is water cooled. The group needs to prepare a stronger analysis as to whether or not any hazards are present due to this design.

- The contingency on the quench protection system cost seems appropriate and is well justified.

- Given the planned industrial procurements the makeup of the AOC should be reexamined and the committee should be asked to comment on the current status of procurement planning including terms and conditions.

Recommendations

16. Given the plan to build two large coils via industrial contract AND build and one large magnet in-house with industrial components, the magnet group needs a labor and management strategy for managing these two diverse but related efforts.

17. Before awarding the design construction contract put in place terms and conditions that create:

    - A well-defined process for change control with agreed on labor rates and profit margins for Fermilab requested changes

    - An agreement on who provides and funds replacement conductor in the event that a coil fails to meet acceptance tests and must be rebuilt

    - A dispute resolution and mediation process

    - A contract oversight plan with hold points and progress and performance payments including penalties/incentives that allows active management of the contract by the project

18. The project should investigate industrial contract management strategy and issues encountered by the ORNL U.S. ITER team

19. Separate the risks for PS, DS, and TS since these have different risks, failure modes, and mitigation strategies

20. Create a failure mode and effects analysis to guide the creation of a risk matrix for the SC magnets. Assign probabilities and costs for each failure mode to create an overall risk and defensible contingency.

21. Roll up the risks from the magnet risk register to create risks managed by the project maintaining separate project risk, mitigation strategies, and contingencies for PS, TS, and DS.

22. KPP's should be adjusted to include the solenoid performance which allows the experiment to achieve its physics objectives.

23. Engage the AOC to provide contract and management guidance to the mu2e magnet group.

24. Examine the schedule for near critical path items and treat these as critical path to insure schedule and cost meet project requirements.

2.4 Muon Beamline

Lead: Jim Kilmer

Contributors: Rich Andrews

Findings

- The muon beamline technical design is well documented in the TDR.

- The muon beamline team is following the Fermilab Engineering Manual and demonstrated that by showing an engineering risk worksheet for the work and sample engineering notes.

Comments

- A Requirements document should be written for the drive system and variable aperture in Collimator # 3, including the estimated number of cycles of motion and the expected lifetime of the collimator and vacuum window.

- The muon beamline team has a long float of nearly two years which they intend to use as time to refine their designs using simulations. Many of the design elements have been driven by the ability to get these simulations done. The project is encouraged to try and finish these simulations as soon as practical in order to finalize the designs. As recently as a few weeks ago a simulation indicated the need for an antiproton window at collimator 1 and another small piece of absorber added to the inside of collimator 1.

- Parts of Mu2e will be installed off project (after KPP). This work will take place after FY2020. This work is coincidently placed during the installation of the Beamline, Target Complex, and Absorber for LBNE. Fermilab management needs to be aware that there is a potential competition for the resources of the laboratory.

- The Muon Beamline WBS is ready for a DOE CD-2 review.

Recommendations

25. There is a concern about the ability to be able to form borated polyethylene into the shape of the outer proton absorber. While a prototype fabricated by a contractor is expensive it may be a very good investment. Simple forming tests should be done on site to investigate forming methods.

26. The vacuum window for Collimator # 3 is currently made out of a low Z material. There is a possibility that the material choice could be beryllium. If the project makes this change then they need to write a safety plan for dealing with this hazardous material.

2.5 Calorimeter

Lead: Adam Para

Contributors: Rich Talaga

Findings

- Detailed analysis of backgrounds and expected performance of the mu2e tracker has established that the calorimeter will play a critical role in rejection of potential background due to mis-identified muons. The required rejection factor of muons is deemed to be 1:200, while preserving high efficiency for electron identification. A successful accomplishment of this task requires energy resolution no worse than 5% and the timing resolution of the order of 0.5 nsec. This performance will be sufficient for the additional functions of the calorimeter: providing an independent off-line trigger and improving the tracking capabilities.

- Geometry of the calorimeter has been optimized and the vanes are replaced by two rings of axial crystals.

- Considerable progress in design, prototyping and test beam studies of calorimetric prototypes including front-end electronics have been conducted for an excellent calorimeter based on LYSO crystals read out with Hamamatsu large area APD's. Due to unexpected cost fluctuations this solution is no longer viable.

- New baseline has been established using BaF2 crystals. These crystals have very fast scintillation component around 220 ns (~10%) and much larger slow component (650 nsec decay) centered at 300 nm. Its application to the mu2e experiment requires a successful development of new photodetectors, with extended deep-UV sensitivity and with greatly reduced sensitivity to wavelength beyond ~300 nm (factor 400 or better) to eliminate slow component of the crystal response.

- A novel type of UV-extended, 'solar-blind' APD's specifically optimized for the readout of BaF2 crystals is being developed by Caltech/JPL/RMD consortium supported by startup funds from SBIR and JPL. First prototypes are expected to be available this Fall.

- A backup (cheaper) solution involving CsI crystals read out by large arrays of Hamamatsu SiPM/MPPC's has been demonstrated to be viable.

- Both solutions are expected to meet the physics-driven requirements.

- On-detector electronics consisting of Amp-HV card, ARM controller have been designed and constructed at Frascati by the SEA electronic department group. They have been successfully tested in test beams using LYSO/APD combination.

- Due to the differences in the bias voltages (70 – 500 – 1800 V for the CsI-LYSO-BaF2) and differences in the signals and noise levels of the crystal/photodetector assemblies the final design of the front-end electronics must await the final selection of the technology, although it is likely that only relatively small modifications to the LYSO-oriented solution will be necessary.

- It is expected that the final choice of the crystal/photodetector technology will be taken no later than March 2015.

- In case of BaF2 based calorimeter there will be 3720 analog signals to be digitized with 200 Msps and 11 bits resolution. A prototype digitizer board has been designed and it is being tested.

- The calorimeter and its electronics will operate in vacuum with very limited access capabilities. This will require use of highly reliable, military grade components and careful design of the boards and their support systems to allow power dissipation through conduction.

- Conceptual design of the mechanical support structure and details of the crystal/photodetector assemblies have been developed by INFN Lecce. An initial FEA has been performed and at least two possible solutions have been identified. These configurations ensure that the mechanical loads on crystals are within the safe ranges for the BaF2 crystals. CsI crystals are more robust from the mechanical stand point.

- Based on the extensive experience of BaBar and CMS several calibration techniques have been developed. Cosmic rays and momentum analyzed DIO muons will provide excellent in-situ calibration. Photodetectors response and light transmission in the crystals will be monitored using laser, whereas the absolute calibration will be provides by 6 MeV photons from the source calibration system. Source calibration will re-use the BaBar technique of photons produced by neutron-activated short-lived fluorinated fluid. Major elements of the source system were salvaged at SLAC and they will refurbished for the use at mu2e.

- Design of the calorimeter system and the construction and installation chain is at the advanced conceptual stage, in part due to the uncertain choice of the crystals and photodetectors. Most of the labor cost estimates are based on previous experience involving similar detectors (BaBar, CMS).

- Major part of the subsystem will be provided as in-kind contribution from INFN. There are on-going discussions regarding the exact scope of this contribution, thus creating difficulty in the understanding of the details of the support required from the DOE funds.

- The schedule presented by the level 2 manager assumes very rapid and positive outcome of the ongoing R&D process and it proposes the CD-3 review for the Fall 2015.

Comments

- It is extremely important that the critical role of the calorimeter of providing a factor of 200 of rejection against muons is identified and understood. This required functionality does not pose very demanding requirements on the calorimeter performance. A detector with perfect time and energy resolution can accomplish 97% signal detection efficiency, whereas a calorimeter with 10% energy resolution and 1 ns timing resolution (factor two worse than design) would achieve 95% efficiency. This is very fortunate given the fact that the excellent calorimeter based on LYSO seems to be out of reach, whereas both alternative solutions considered will provide better than adequate performance.

- Development of BaF2-based calorimeter would be a very valuable contribution to our field. It is challenging and it requires development of 'solar blind' deep UV sensitive photodetectors. Its principal advantage for the mu2e experiment comes from its very fast response time (fast component) making it a viable detector for the PIP II era.

- Development of an UV-sensitive photodetector is of great interest far beyond the mu2e experiment. Collaboration of Caltech/JPL/RMD is very promising and it should be supported to the extent possible. This route presents significant risks within the timeframe of the mu2e experiment, even if the underlying technology will prove workable. (Who will do the thinning? Atomic layer deposition? What is the long term behavior of such APD's? Their radiation resistance?)

- Deep UV sensitivity requires no material in front of the active layer of the photodetector and it is proposed to use them 'bare' (i.e. without any protective coating). This is a very challenging proposition.

- A layer of UV-transparent optical grease is proposed to be used between the APD surface and the crystal. This is a very risky proposition. There are extremely strong electric fields at the surface of the APD and they produce movements of ions in any materials in close proximity to the surface of the APD which can influence the proper functioning of the APD. Trace amounts of metal ions (silver, and potassium seem to be particularly dangerous) or any moisture may cause a malfunction. These processes may have adverse effects on the performance of the detectors in long timescales.

- It would extremely desirable to construct and test in the beam a complete prototype involving the final crystal, photodetectors and electronics before proceeding with the final purchase order. This is not consistent with the proposed schedule. In particular the sensitivity to the neutron-induced damage of the crystals ought to be studied.

- Given the new and relatively modest performance requirements for the calorimetry the calibration requirements should be re-visited. It is very likely that the in-situ calibration by a combination of cosmic rays and the momentum analyzed tracks may prove (more than) adequate. Elimination of the source-base system could be a major simplification of the subsystem.

Recommendations

27. Update the schedule and develop a decision path to select the crystals and photodetectors as early as possible. Develop a plan of targeted R&D studies to provide the necessary inputs for the decisions impacting the final design in time for the proper preparation for the CD-3 review.

28. Develop a strong case for the Italian funding agencies to stress the critical importance of the calorimeter and the leading role of INFN institutions in achieving the ultimate sensitivity of this experiment.

29. Finalize the MOU with the INFN as soon as possible. In particular develop a very detailed list of deliverables and responsibilities to allow for a proper development of the construction and installation plan and defensible cost estimates.

2.6 Cosmic Ray Veto

Lead: Rich Talaga

Contributors: Adam Para

Findings

- Simulation of 28 billion cosmic ray muons, corresponding to 2.2% of the muons over the total live period, show that a CRV inefficiency of no worse than 10^{-4} is required. The simulation identifies regions where muons produce conversion-like electrons that mimic the signal.

- Targeted simulations have been performed that cover the total live period. These simulations focus on particular portions of the CRV coverage in places where there are unavoidable holes, such as the TS "hole" where no conversion-electron like events originate. However, there are ~ 50 muons mimic conversion-electrons which the CRV cannot eliminate and they must be removed by the calorimeter and tracker.

- A penetration through the CRV for cryogenic pipe has been added to the design. Targeted simulations indicate that this will not have an adverse effect on the expected background levels.

- Extensive simulations by the Neutron Working Group have shown that the rates from beam-associated neutrons and gammas are higher than the earlier estimates extrapolated from MECO studies.

- The Project has added shielding to reduce the beam-associated backgrounds. Additional shielding can be added by replacing standard shielding blocks with barite concrete, without changing the shielding dimensions.

- In order to prevent excessive dead time due to neutron-induced backgrounds the veto signal threshold has been raised. Fiber diameter has been increased to 1.4 mm to maintain cosmic ray detection efficiency. This will assure that the CRV inefficiency is at 10^{-4} (or better) for the planned threshold.

- CRV modules have been augmented by adding a fourth scintillation layer in response to the higher rates. In addition, scintillator layers are now 2 cm thick, double the prior thickness, and aluminum absorbers between layers are thicker to absorb through-going electrons.

- The energy threshold and veto signal will be applied at the data acquisition stage and not in real time.

- The CRV is based on extruded plastic scintillator with a co-extruded reflective cap, a well-established technology at Fermilab. The SiPM photodetectors and all electronic components are commercially available devices.

- Photodetectors and front-end electronics have adequate radiation hardness against ionizing radiation. Exposure of the electronics to neutrons is a concern and neutron exposure tests are planned.

- FPGAs will be reloaded periodically to mitigate possible neutron-induced failures.

- A plan to produce and assemble detector modules has been developed.

- The major electronics components have been identified and tested individually.

- Management staff been increased with addition of L3 managers for photodetectors and installation.

Comments

- Recommendations from prior reviews have been addressed. One of the recommendations regarding delta ray production by muons is beyond the CRV schedule and budget, but the CRV team has identified an independent investigation that is in the process of verifying those rates.

- CRV modules at the downstream end of the detector (CRV-D) may not have sufficient coverage. This area may require one or two additional modules. These additional modules are off-project, which may have to be made after the assembly factory is decommissioned.

- Prototypes should be built to verify assembly methods and module performance.

- Working prototypes should be built to finalize the assembly method and identify means to streamline production. Efficient means to remove and repair di-counters with fiber problems should be developed.

- Photodetectors are turned off during beam spill to avoid extraordinary rates. There are transients when this happens. Baseline restoration may be an issue and needs to be addressed.

- Working prototypes of the readout electronics chain should be built and tested before CD-3.

- The presentations at this Review are consistent with the TDR.

- The CRV is technically sound and the management team is capable to execute this task. The CRV is ready for the CD-2 review.

Recommendations

30. Production of a suitable number of spare modules supported by Project funding should be considered.

2.7 Tracker

Lead: Kevin Pitts

Contributor: Tom LeCompte, Eric James

Findings

- The Tracker is an integral part of the Mu2e experiment.

- System Assembly procedures and components have been specified.

- Labor estimates per task are based upon prototyping and prior experience.

- Costs are well documented. Some estimate levels are out-of-date.

- In some cases where there is a specific design choice to be made, risks are carried in the form of estimate uncertainty.

- Some risks have been retired. The team has considered additional risks.

Comments

- The design directly addresses many challenges: tracking in vacuum, limited space and limited access. Simulation has been successfully utilized to understand backgrounds, performance and drive design considerations.

- All aspects of the system have capable personnel. Managers of the system are extremely knowledgeable. An impressive amount of R&D and design work has been carried out to date. The probability of this group successfully building and operating this device is very high.

- The cost estimate for the Tracker is reasonable. The contingency assigned on M&S is appropriate.

- Recent design changes (number of stations) need to be propagated through the BOEs.

- The amount of labor per task is appropriate, but the overall timelines need to be revisited and task durations reassessed.

- The risk registry does not fully reflect the level of thought and planning that has been performed.

- The team should continue with current prototyping plan to finalize the design and draw upon the variety of expertise that exists within the project.

Recommendations

31. For CD-2, update estimate levels and task durations to be consistent with current knowledge and to better match the evolution of the project and available labor. Document additional risks associated with this project.

2.8 Trigger and DAQ

Lead: Eric James
Contributor: Tom LeCompte, Kevin Pitts

Findings

- The DAQ system is required to collect and assemble data from the different detector elements for online analysis and potential transfer to offline storage.

- Online processing of the data from the time slice associated with each proton bunch is required to make a triggering decision on whether to write the data into offline storage for future analysis.

- Because of the potential large size of data from the cosmic ray veto system, data from this system is read out only for time slices selected by the trigger algorithms.

- The proposed architecture is multiple DAQ servers, each of which has connections from up to 12 readout controllers on the detectors. The data fragments collected in each of the servers are passed and collected into one of the individual servers for online processing.

- The fabrication of the readout controllers associated with each detector system is the responsibility of the individual detector construction projects.

- All of the hardware required to construct the DAQ system are commercial products that can be purchased directly.

- The majority of the effort associated with the trigger and DAQ project is in software development. The run control software is based on the artdaq framework.

- Three non-negligible risks have been identified including insufficient resources for software development, the potential need for additional online processing power, and higher than expected data input rates.

- The estimated cost for the Trigger and DAQ system is $6.1M with an assigned contingency of 38%. M&S estimates are typically based on quotes or catalog prices. Labor costs are based on experience from previous experiments on similar software development efforts.

- Three periods of software development have been incorporated into the schedule with a 2015 milestone for completion of a pilot system, a 2018 milestone for the completion of the full production system, and a 2020 milestone for demonstration of the full system through cosmic ray tests.

Comments

- The planned architecture is sensible and the use of commercially available components in constructing the system is strongly supported.

- Taking advantage of the artdaq framework, which has been successfully used in the implementation of run control software for the Darkside experiment and various LBNE test beam activities, is a logical choice and will accelerate software development and reduce costs.

- The assembled team is a strong one, and the committee has confidence in their ability to successfully complete the project.

- The identified risks seem reasonable and the proposed mitigations are straightforward and easily quantifiable (purchases of additional hardware or additional professional software support).

- The methodologies used to create the cost estimate seem sound and the assigned cost uncertainties seem reasonable.

- The defined milestones are too vague for accurate tracking of project progress.

- The completion of the full production system in the current schedule occurs several years before it is actually needed. It is not clear that the full system is even required for the full detector cosmic ray test in late 2019.

- Uncosted labor in out-years should be incorporated into the project schedule.

- The DAQ group should interface with the DAQ effort for the Extinction Monitor system to fully understand needs, requirements and interfaces.

- University-based collaboration should be pursued as soon as possible.

Recommendations

32. Milestones need to be better defined in terms of the hardware and software functionality required at the end of each development stage (*e.g.* for the initial pilot system; for the system used for tracker development; for the system used in the full detector cosmic ray test; and for the full production system). The milestones should align with the requirements of the other subsystems of the Mu2e project.

33. Hardware purchases for the full production system should be moved as late in the schedule as possible to obtain the maximum computing power per dollar. Machines are typically under warranty for three years, and the experiment would not want to be in a situation where the warranties were expiring just as data taking is commencing.

3.0 Cost and Schedule

Lead: Lynda Gauthier

Contributors: Laurie Casarole, Sherese Humphrey, Thomas Baumann-Neylon, Al Zeller

3.1 Cost

Findings

- The project has a BAC of $217.6M and TPC of $270.8M.
- Contingency is the combination of estimate uncertainty and risk exposure. The project has $53.2M of cost contingency which is 24% of BAC or 31% of remaining budget (work).
  - Cost estimate uncertainty totals $48.0M
  - 90% confidence level cost associated with risk is $5.2M
- The basis of estimate (BOE) is well documented and the assignment of contingency is consistently applied throughout the project using a defined set of rules.
- The project is waiting to receive a funding profile from the DOE to support the $270.8M TPC. Once the funding profile is available, the project plans to adjust the baseline plan to fit within the profile.
- Obligations are tracked at the point in time when purchase orders are issued/awarded.
  - Accruals are generated for material receipts upon delivery. The L2 construction manager has developed an approach to capture GC performance within the schedule to validate accrual values each month.

Comments

- Based on the estimate uncertainty model in place, the cost estimate quality is at an appropriate level for this stage of the project with 88% of the cost estimate at level 4 (preliminary) or stronger.
- CAMs were well versed in the technical scope and were proficient in its presentation. However, they were not as proficient when answering questions about cost, schedule and EVMS. Managers should try to be at the same level of proficiency by the CD-2/3b review.

Recommendations

34. The project should conduct a review of the BOE's including a cross-walk to the schedule to ensure all of the costs are reflected correctly. This review should be done by the CAMs themselves in order to develop their proficiency in cost and schedule drill downs and, more importantly, so CAMs 'own' their scope, cost and schedule baseline plans.

3.2 Schedule

Findings

- The integrated schedule is resource loaded and contains: 6022 activities: (4,324 Work Packages [3,212 current budget, 758 contracted labor/material purchases, 354 obligations]); 494 milestones; and 25 constraints).
- The project has 30 CAMs who manage 71 Control Accounts.
- The project is divided into 10 stand-alone projects (1 for each WBS and 1 for Operations which occurs after KPPs have been achieved). This structure prevents users of the schedule tool from "overwriting".
- Each resource loaded schedule was developed independently, and then integrated into a master schedule.
- The schedule contains 24 months of schedule contingency, beginning at the early finish date in December 2020 and extends to the CD-4 date in December 2022.
- Estimate uncertainty has been assessed at the activity level.
- The BOE for WBS 475.02.07 within the Accelerator reflects current estimates, those estimates have not been reflected in the schedule.
- The project has been collecting schedule performance for the past six months. The CAMs were familiar with the turnaround document (mechanism used to collect performance).
- Some internal and external interfaces (GPP, AIP, Muon g-2) exist within the schedule.
- Some instances of open logic exist within the schedule baseline.
- Earned value is recorded for material receipts/deliveries after defined acceptance criteria have been met.

Comments

- The project controls team on the project is very competent and knowledgeable.

- Simulation activities for costed resources should be reflected as discrete work (rather than LOE) in the plan to ensure that performance is being accurately measured for this work.

- Schedule activities with open logic should be corrected. Interfaces between external and internal entities need to be established within the plan to ensure accurate relationships so that the project's critical path is accurately depicted and understood between the PM and CAMs.

- The project should review those control accounts that exceed the allowable ratio of LOE to discrete activities within a control account. Having discrete activities mixed with high volume of LOE activities could hide schedule performance. The ratio below 15:85 is a good practice to follow. Consider planning LOEs in separate control accounts if the ratio cannot be successfully planned.

- The L2 manager for Construction was well aware of the inner workings of the Docdb and led the effort while the drilldown was being performed.

- The schedule contingency of 24 months appears to be adequate for the project.

- General housekeeping should be performed on the integrated schedule. The schedule view log should be analyzed to close open ends (activities without predecessor and/or successor) and out of sequence logic.

- The use of lags in the schedule should be fully explained using the notes field in P6 prior to the CD-2/3b review. Having too many lags could impact the critical path analysis.

- Activities with an assigned earned value technique of 'percent complete' which are longer than 44 days (two reporting periods) in duration should have defined objective measures/steps. This should be done for activities within a six-month look-ahead in the schedule.

- There is a mismatch between some BOEs and P6. This is recognized and the path forward is under discussion. For example, the accelerator management team stated there is $1-2M more in the BOEs for the magnets and power supplies than is shown in the schedule.

Recommendations

35. The project should conduct a review of the BOE's including a cross-walk to the schedule to ensure all of the cost estimate is loaded into the schedule properly and supported by the BOEs. This review should be done by the CAMs themselves in order to develop their proficiency in cost and schedule drill downs and, more importantly, so CAMs 'own' their scope, cost and schedule baseline plans.

4.0 ESH&Q

Lead: Mike Andrews
Contributor: Jemila Adetunji

Findings

- The Project Hazard Analysis, ISM Plan, and Security Vulnerability Assessment have been developed.

- There is a well-documented Quality Assurance Program Plan in place for the project, created in 2010 but not updated since 2012.

- The final NEPA determination of a categorical exclusion was issued by DOE FSO on 6/12/12.

- The Project Management and Execution Plans address ESH responsibilities and Integrated Safety Management.

- The Mu2e ESH Coordinator is integrated into the Project coordination meetings relating to project management, design, construction, and installation activities.

- The ESH requirements detailed in the Mu2e and MC Beamline conventional facilities RFP were not reviewed by the Mu2e Project ESH Coordinator, ESH Section, FESS-ESH, or PPD/ESH prior to being issued for bid. The RFP presently allows for the assignment of the construction sub-contractor ESH Safety Representative, who provides ESH support and oversight, for the construction sub-contractor activities to the construction sub-contractor site superintendent. The document also does not define any requirements for ESH credentials or certifications (30Hr OSHA) for the Subcontractor Safety Representative.

- The FESS-ENG Section is planning to hire an independent ESH consultant to provide supplemental ESH support and oversight for the conventional facilities construction activities, if problems exist.

- Fire and Life Safety Assessment has been completed and documentation is in place.

- The Project has received Preliminary TLM Safety Approval on 4/29/14 for the Fermilab ESH/QA Section Head.

- The Project has received a preliminary shielding assessment approval on 6/16/14.

- There is no designated QA Manager for the project as defined by the project's Quality Assurance Plan.

- The Quality Assurance Plan defines the assignment of quality levels to suppliers which are evaluated to determine their ability to provide acceptable items and services. There is a project Technical Board that does exist which defines supplier criteria/requirements.

- L2/L3 Managers are responsible for managing Quality Assurance verification and validation activities.

- The TDR has Quality Assurance sections for each project sub system which highlight QA requirements. The TDR discusses, in detail, in process ESH&Q checks, risks, mitigation, reference to procedures.

- There are no specific Quality-related risks within the Risk Register and was noted that those risks are not managed within the Risk Register but within the Quality Plans.

- Great work and effort has been done on the Quality Control parameters and documentation of the Solenoid system.

- There is an extensive Quality Assurance Program Manual written for the Mu2e Cosmic Ray Veto Module Factory.

- The Breakout talks given by the L2/L3 managers cover ESH and QA/QC aspects of their particular subsystem.

Comments

- The Project Hazard Analysis, ISM Plan, and Security Vulnerability Assessment have not been signed and approved.

- The Construction Project Safety and Health Plan has not been developed which is required for CD-3 approval. There has been some confusion relating to meeting this requirement between the DOE 413.3B Order and the Critical Decision Matrix requirements.

- The proposed construction sub-contractor ESH oversight support detailed in the present conventional facilities RFP is currently insufficient based on the size, high risk nature of the work, and the criticality of the project.

- The Mu2e Project ESH Coordinator and ESH Section should be included in the construction RFP review process prior to releasing the documentation for bid.

- Proposed Project ESH Construction Oversight is not fully developed but should be defined in the Construction Project Safety and Health Plan.

- As part of the review of the project's Hazard Analysis Report, it was noted that the Barium Fluoride crystals was not discussed within. It was suggested to the project team to add this within the HAR.

- The Project Hazard Analysis risk data needs to be evaluated by ESH support personnel to verify appropriate pre and post mitigation categorization.

- The Mu2e ESH Coordinator's presentation should include a slide with an organization chart detailing Project and matrix ESH support.

- The QA Manager has clearly defined roles and responsibilities within the Quality Assurance Plan which are vital to the successful execution of the plan, but there is no responsible person for this role. The project has identified the importance of this gap and has an opening to fill this role through PPD and has budget allocated for this role.

- The project Quality Assurance Plan does not accurately reflect the current state of affairs (i.e. what happens in the absence of a designated QA Manager or how the defined roles and responsibilities for this role will be managed in the absence of this role). There is a need for all quality aspects of the project to be managed at a high-level to ensure that the necessary interfaces are present (i.e. checks and balances) as well as an established issues management process.

- Procurement was not aware of the defined supplier quality levels, as referenced within the Quality Assurance Program Plan nor was there documentation available to support the quality level assignments to suppliers.

- The project should post the Mu2e R&D Conductor Performance and Production Readiness document (4221) on the review website.

- The Project QA Manager, once appointed, should review the quality plans and details discussed within the TDR then update the QA Plan.

- The Project presently does not have QA risk document which contains all of the identified QA related risks/issues and available for the project team to view. It is not clear which specific quality risks have been identified, assessed and mitigated.

- Breakout talks should address procedures for handling potential incoming inspection /acceptance criteria failures.

- It would be helpful to the review team to have some of the established documentation and procedures that have been written within the subsystems and referenced within the TDR available for review. Also Breakout talks should reference some of the highlighted documents within the examples provided.

- The Plenary and Breakout talks refer to the project's Quality Assurance Plan (Mu2e DocDB #677) as the Quality Management Plan - this should be made consistent - either one way or the other.

Recommendations

36. The conventional facilities Mu2e and MC Beamline RFP documentation (Exhibit A, Addendum A) should be modified to incorporate a separate ESH staffing requirement for a Construction Sub-Contractor Safety Representative.

37. The Construction Project Safety and Health Plan needs to be developed to incorporate both construction and installation activities with approval prior to CD-3b.

38. The Project Hazard Analysis, ISM Plan, and Security Vulnerability Assessment need to be approved and signed prior to CD-3b.

39. Update the QAP to reflect the current state of affairs, eliminating activities that are not being performed, and update obsolete references. Specifically refine the roles and responsibilities for quality regarding who is responsible for the project's QA Program in the absence of the project QA Manager role.

40. Quality assurance risks should either be documented in the Project Risk Registry or in a separate QA document and tracked.

5.0 Management

Lead: Marc Kaducak

Contributors: Brenna Flaugher, Elaine McCluskey

Findings

- The project management office staff as well as L2 and L3 managers are identified and in place with the exception of a permanent quality manager.

- The Mu2e project depends on a suite of GPP and AIP projects collectively known as the Muon Campus Program, which is managed by the Accelerator Division.

- INFN plans an in-kind contribution of 1/3 of crystals, ½ of photodetectors, laser system, mechanics, and all FEE/Digitizer Electronics to the Calorimeter.

- The project includes 71 Control Accounts managed by 30 CAMs. The values of control accounts range from $4k to $14M.

- The project has not been given a funding profile from DOE.

- Mu2e proposes to request CD-3 for the Conventional Construction and parts of the accelerator including Instrumentation and Controls, Radiation Safety, and Delivery Ring RF at the upcoming DOE CD-2/3 review in August 2014. A series of follow up CD-3 mini-reviews will be conducted as final designs are completed for other elements.

- Key Performance Parameters (KPPs) to reach CD-4 are documented in the PEP at both the threshold and objective levels. The scope/cost/schedule to reach the objective KPPs are presently in the project's working baseline. The cost delta between threshold and objective levels is about $1M.

- A set of required documents for the DOE 413.3B process and for the FNAL project management system was presented. Documents required by DOE include the Acquisition Strategy, PEP (including Safety/Vulnerability Assessment, life cycle costing, discussion of alternatives), Risk Management Plan, TDR, Hazard Analysis, QA program, and NEPA determination.

- The project has identified risk, performed qualitative and quantitative risk analysis, Since CD-1 they have retired 29 risks, spent $6M to mitigate risk, and realized 6 risk opportunities to earn $1.7M. Forty-eight risks are actively managed at the time of the review. After a Monte Carlo analysis based on these risks and using a 90% confidence level, the project is carrying $5.1M in cost contingency and 24 months of schedule contingency.

- The project has nearly 500 milestones. The project has 24 months of schedule contingency on CD-4 which is a Level 0 milestone. The 3 L1 milestones are held by the DOE OHEP program director and include 12 months of contingency. The 24 L2 milestones are held by the DOE Federal Project Director and have 6 months of contingency. The 23 L3 milestones are held by the Fermilab Directorate and have 3 months of contingency. The 71 Level 4 milestones are held by the Project manager and have 2 months of contingency. The L2 managers have 205 milestones (1 month contingency) and 76 of those are already complete. The control account managers hold 55 L6 milestones and these have no contingency.

- The higher level milestones are sometimes associated with lower level milestones.

- Within the L2 subsystems there are some large gaps (>6 months) in the milestones held by the project manager and in the milestones held by the subsystem managers.

- The Calorimeter subsystem, which has a large in-kind contribution has only 4 L4 milestones between Jan. 2015 and March 2018.

- The Project has performed engineering risk assessments as prescribed by the Fermilab Engineering Manual for many of the components. The output of this analysis defines the formality of the engineering process that should be applied (graded approach).

Comments

- The project management staff is experienced and capable of successfully executing the project. The Deputy Project Manager is transitioning to a new role of collaboration co-spokesperson and the project plans to fill the resulting vacancy in August. A permanent QA manager also needs to be identified.

- The Muon Campus program GPP and AIP projects are needed for the g-2 project in advance of when they are needed for Mu2e and appear to be on track. Milestones for the Muon Campus projects in the Mu2e schedule include>1yr float.

- Installation of Mu2e will likely overlap with g-2 operations. The project and the Lab should work together to minimize associated cost and schedule impacts to the project.

- The project stated that the planned contribution to the calorimeter from INFN is 1/3 of crystals, ½ of photodetectors, laser system, mechanics, and all FEE/Digitizer Electronics and that this scope has been stable for over one year. The schedule should include more milestones for the INFN work to monitor the work at regular intervals.

- The project recognizes the need to carefully choose CAMs and control accounts and recently reduced the quantity of CAMs to 30 from 48. Each CAM will require EVMS and CAM training and must keep up with evolving practices. The project should consider further reducing the number of CAMs and control accounts to improve efficiency of managing EVMS related activities.

- Key elements of the PEP such as the funding profile, change control approvals, and the KPPs need final agreement. FNAL reorganization needs to be reflected in the PEP and PMP. Other project documentation needs a QA check to be sure all documents are updated and references between documents and those that include cost/schedule information are correct.

- The format and content of the monthly reports should be improved. Generally presentation of obligations and reqs in progress are helpful since they are the earliest indicators of budget status. Presentation of the cumulative usage at each sign-off level and the total remaining contingency should be included in the monthly reports. Milestones completed each month and upcoming milestones are an excellent way to communicate progress and provide early warning of future issues. Remaining schedule float on the CD-4 milestone should also be included.

- The project has a well-developed set of interface documents in docdb that would provide useful documentation for the CD-2 review. Development of a consolidated interface matrix will be useful as the project progresses and would also be useful for demonstrating to reviewers that all the interfaces were identified and documented.

- The project has developed a set of 30 requirements documents and a very nice system for managing the approvals and sign-offs. These requirements contain both science and technical requirements for individual subsystems. The requirements are also in the TDR. A single science requirements document would make it easier for the project team and reviewers to understand the critical scientific performance requirements and the flow down of these to the technical requirements. Clearly documenting these relationships will be useful as the project develops if/when specific technical requirements are later identified as cost or schedule drivers or opportunities for cost or schedule reduction.

- The project has plans in progress for the transition to operations. Work with the lab to collect these into a standalone transitions to operations document that would be a useful way to communicate the project expectations for operations support. If it is ready for the CD-2 review it would help reviewers understand this phase in more detail.

- The project has responded to the recommendations from all previous reviews. It would be helpful to include dates for each response in the response documents. Review of the CD-1 recommendations and update of their status may be useful.

- The plenary presentations were well prepared and thorough. Cost plots were clear and effective. The schedule plots could be improved by clearly indicating the schedule float (e.g. a large red arrow and text with the number of months). All of the plenary speakers should introduce themselves and give a brief statement of their relevant experience.

- The difference between threshold and objective KPPs correspond to different stages of readiness for operation. Threshold KPPs were designed to avoid potential schedule risks due to activities outside the project's control. Besides the $1M delta between the threshold and objective KPPs, the project does not have a list of candidates for scope reduction, i.e. scope contingency. The project should be prepared to discuss scope contingency at the upcoming DOE CD-2/3b review.

- The project stated that additional scientific resources are needed for trigger and DAQ development. There are risks in the registry for inadequate or unavailable AD engineering and DAQ development (uncosted) resources. Other resources required for the project are available.

- Lack of a funding profile severely limits the project's ability to complete preparations for the upcoming Independent Cost Review and DOE CD-2/3b reviews. The project expects to receive a funding profile soon, but if it does not arrive before 15-Jul-2014 and/or its content is incompatible with the project's current plan then it will be very difficult to prepare a compatible baseline plan for the DOE CD-2/3b review. The profile is already very late with respect to the Independent Cost Review and the project should consider rescheduling this review until after the DOE CD-2/3b review or coincident with it.

- The point estimates in the risk register don't always match those on the linked risk forms. These should be made consistent. The risk register needs to be reviewed bottoms-up to ensure that all risks have been identified and sufficiently analyzed and quantified. No cost contingency has been identified for unknown unknown risks.

- The application of the Fermilab Engineering Process does not appear to be fully consistent across the project. Components with high technical, schedule or cost risk should perform more formal engineering design reviews, incorporating independent reviewers from outside the project.

- The FNAL procurement department representative is highly integrated with the project team and has been informed of all upcoming significant procurements. The project has prepared a procurement management plan and vendor oversight plan that list the major procurements and describe responsibilities for procurement related QC plans. Interaction between the project and the procurement department seems to be quite effective.

- A plan for grouping and scheduling CD-3 mini-reviews was presented. Further consolidation would be beneficial in terms of availability of reviewers and general efficiency. The project should conduct internal subsystem design reviews as part of the engineering process and in preparation for these mini-reviews.

- The project is not yet engaging the CAMs in performance measurement and analysis. CAMs received EVMS training but have not received any site-specific or project-specific training to teach them the monthly steps for performance reporting and analysis. The steps in the month-end status cycle should be documented and communicated to CAMs so they understand their role and responsibility for performance reporting and analysis. CAMs should also be trained on the process for baseline change control. Project Controls personnel can assist the CAMs and act as the CAMs first point of contact for process questions and support.

- The project should review the milestone strategy and identify additional milestones. It is generally helpful for the higher level milestones to be a subset of the next lower level. This alerts each level of management to problems before they rise to the next level of management. The milestones monitored by the L2 managers should be frequent, roughly one per month per subsection of the L2 section. Long gaps (for example during development or procurement tasks) should have intermediate milestones so that problems and solutions can be identified early. The PM should have at least one L4 milestone/per L2 section per month so the PM gets the pulse of the entire project; this is the PMs early warning system. The L4 milestones should be a subset of the L5s. The L3 milestones are subset of the L4 milestones with different levels of contingency. Roughly 1-2 L3 milestones per L2 section every 4-6 months would give the Lab management a clear picture of project status. Milestone levels are inconsistent between the signoffs in PEP and the P6 schedule and will need to be reconciled before the DOE CD-2/3b review.

- The Accelerator System team identified $1-2M of scope that had been estimated but is not yet included in the project's cost estimate. The committee feels that the contingency on the Solenoid System is inadequate and that an update of project risks across all systems is needed, which would likely result in a requirement for additional risk contingency. Finally, a risk contingency component for the "unknown-unknown" risks is not currently included. Adjusting for these items could result in a TPC increase of $5-10M.

- Tasks with significant uncosted or in-kind contributions should have a higher milestone density than costed tasks since cost information will not be used to monitor progress.

- The committee feels the project can be ready for CD-2 after addressing the recommendations in this report.

- While the Accelerator System Instrumentation/Controls, Radiation Safety, and Delivery Ring RF are ready for CD-3, they are not urgently needed in the project schedule and the Accelerator System as a whole is not at the final design state.

The project should consider consolidating the CD-3 request for these components with requests for other Accelerator Components currently planned in Jan.2015. This would limit the CD-3b request in August to the civil construction.

Recommendations

41. Create a single Science Requirement Document that gathers all the science requirements and traces their relationships to the technical requirements for the CD-2 review.

42. Post interface documents and consider creation of an interface control matrix prior to the CD-2 review.

43. Review the various higher risk components of the project to assure that all engineering and design work is being performed consistent with the Fermilab Engineering Manual.

44. Consider reducing the quantity of CAMs and control accounts.

45. Develop and implement a comprehensive milestone strategy prior to the CD-2 review.

46. Update the PMP, PEP, TDR, Configuration Management plan, and other project management documentation prior to the DOE CD-2/3b review.

47. Consider delaying ICR until after or coincident with the DOE CD-2 review.

48. Work with DOE to obtain a funding profile ASAP. It should be made available at least five weeks prior to the DOE CD-2/3b review.

49. Develop explanation for project's approach to scope contingency for CD-2 review.

50. Review the risk register and associated risk forms prior to the CD-2 review.

51. Consider requesting CD-3 approval for the conventional construction only.

52. Proceed to the DOE CD-2/3b review after addressing recommendations from this review.

53. Resolve the apparent discrepancy in the bottom up Accelerator System cost estimate and the estimate in P6/Cobra, re-evaluate the bottom up risk analysis, and include an appropriate contingency for "unknown-unknown" risks. Adjust the cost estimate to accommodate these items, which taken together could increase the TPC estimate by a total of $5-10M.