



Closeout Presentation

Director's Conceptual Design Review of the Mu2e Project

May 3-5, 2011

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Executive Summary

The overall design maturity for the Mu2e experiment is at the conceptual level and consistent with the detail necessary to support a DOE Critical Decision 1 (CD-1). The design is technically adequate for this stage of the design process. In some subsystems the design is equivalent to advanced conceptual design and in a few subsystems some additional design progress is necessary for DOE CD-1 requirements, e.g., sky shine shielding and the e-berm. A global evaluation of the entirety of the design across all subsystems provides confidence that the conceptual design is an adequate basis for moving to preliminary design and that the design will ultimately meet the Mu2e experiment requirements.

A general concern of the committee is the status of simulations. While there is progress on simulations there is more work needed to justify design choices and to support the advertised performance of the experiment.

The draft Conceptual Design Report (CDR) and supporting documentation is generally adequate to support this technical review of the conceptual design. The presentations and discussions with the committee were extremely productive and helped to fill in gaps in the documentation. It will be important to continue to develop and approve additional supporting documentation for the reviews later this summer, e.g., R&D and testing plans for Calorimeter and Tracker, interface control documents, and the additional requirements documents. There were some inconsistencies in the presentation of information in the draft CDR that need to be resolved before the document is finalized. Additional work preparing simulations and detailing R&D and prototyping plans is necessary to transition to preliminary design and to reduce the overall risk.

A lack of resources is constraining current progress and the adverse consequences to schedules will grow given competing demands from other experiments and programs. The potential addition of the g-2 experiment will further complicate this issue. FNAL management should undertake a global assessment of the resources required for the upcoming suite of experiments (and the resources available), establish priorities, and identify scope that can be outsourced.

The project is resource constrained and additional resources are needed to prepare for successful CD-1 reviews and transition to the preliminary design phase of the project. The project should develop a plan for adding resources to the Mu2e subsystems and improving the overall integration effort.

The schedule for CD-1 reviews this summer is realistic based on the committee's assessment of the current maturity of the Mu2e technical design.

1.0 Introduction

A Director's Conceptual Design Review of the Muon to Electron Conversion Experiment (Mu2e) Project was held on May 3-4, 2011 at the Fermi National Accelerator Laboratory. The object of this review was to assess the status and adequacy of the overall Mu2e conceptual design effort to meet the requirements for a DOE Critical Decision 1 (CD-1) "Approve Alternative Selection & Cost Range". The charge included a list of topics and 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.

Each section in this closeout presentation 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 remainder of this presentation has the 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 Mu2e Working Group Meetings (WGM). A response to recommendation(s) is expected and actions taken will be reported on during future reviews

2.0 Accelerator I

Lead: Paul Derwent

Contributors: Kevin Brown, Mike Church, Keith Gollwitzer

Findings

- Considerations for accommodating g-2 would deeply affect the Mu2e proposal for both technical and cost components.

Comments

- Overall scheme is sound and capable of delivering beam requirements with low technical risk; though expect designs to continue to evolve.
- Simulations need to continue to grow in sophistication, including non-linearities and other real world effects.

Recommendations

1. Do value engineering and management to investigate cost and operational impacts on the APB injection scheme (direct Booster to Accumulator) versus the boomerang injection scheme (Booster to Recycler to Accumulator) for the CD-1 review.

2.1 Beam Transport to the Accumulator

Findings

- A complete and coherent set of presentations on beam transport to the Accumulator was made.

Comments

- Using the Recycler as a long transfer line implies the beam goes through 4 fast kickers in 15 microseconds with incumbent possible emittance growth.
- A good criterion for beam loss based on beam-induced activation of elements was presented.
- It was not clear to the committee that the new beamline from Recycler to P1 is compatible with SY120 operations.
- We note that there is not a uniform characterization of apertures or common coordinate system for the transport.

Recommendations

2. Include an injection damper in the Accumulator in the CD-2 baseline plan.
3. Agree on an acceptable aperture definition and use it consistently to define what aperture improvements need to be made for the CD-2 baseline plan.

2.2 Pbar Rings

Findings

- A complete and coherent set of presentations on RF manipulations and hardware, beam aborts, kickers, and beam stability were made.
- Results on calculations for anticipated most troublesome instabilities were presented. The microwave instability in the Accumulator will require active RF feedback. Transverse coupled mode instability may require active control.
- Necessary beam manipulations require 5 kicker systems and 4 RF systems.
- All kicker and septum supplies will need to be rebuilt to handle the associated repetition rates. Most pulsed devices in the tunnel need active cooling.

Comments

- Beamline space is at a premium and many new components are destined for zero dispersion regions of the rings. Location assignments have not been made. Reserve real estate for dampers.
- Service building and penetration space is at a premium and many new components are destined for existing service buildings. Location assignments have not been made.
- All RF manipulations appear sound and an extrapolation of existing operational manipulations.
- We are concerned about the long charging time of the Debuncher abort and associated time window with lack of protection of the extraction septum wires.
- The biggest technical challenge is the Accumulator Injection Kicker, with 57 nsec fall time, location in the Accumulator vacuum, and the high power vacuum feed through.

Recommendations

4. Write a vacuum specification for the Accumulator and Debuncher to be used for the CD-2 baseline plan.
5. Make a real estate map for new components both upstairs and downstairs for the CD-1 review (to see whether more service building real estate is required).

2.3 Extraction

Findings

- A complete and coherent set of presentations on resonant extraction and monitoring was made. Much technical progress was shown.

Comments

- RF knock out appears to be a promising technique but additional feedback systems for spill control could be considered (e.g., quadrupole regulation).
- JPARC and CERN have made advances in electrostatic septum designs that have thinner effective septum thickness and are more robust. An R&D plan needs to be developed for the extraction septum.
- The extraction septum location is a design single loss point. 2-5% is 500-1250 W loss underneath the AP30 service building.
- Requirements document specifies a 50% variation on pulse-to-pulse spill intensity. Current solution does not meet this specification.
- Developing high impedance, low bandwidth wall monitor to be used in feedback. Progress so far looks promising. A secondary emission monitor could be considered as an alternative.

Recommendations

6. Investigate chromatic slow extraction for the CD-2 baseline plan.
7. Ripple measurements on main Debuncher circuits should be made for the CD-2 baseline plan.

2.4 Extinction

Findings

- Extinction monitoring as a two-step solution was presented, with a fast time scale (~10 sec) for the Debuncher and a slow time scale (~1 hour) for the experiment.
- Extinction is done with momentum collimation in the Debuncher and an AC dipole in the external beamline.

Comments

- Simulations did not include several possible ways to populate the out of time beam.
- Debuncher collimation is immature and needs attention.
- As the Accumulator and Debuncher have different periods, the Debuncher RF has a phase jump every Debuncher injection. The AC dipole supply needs to maintain phase lock to the Debuncher RF.
- The choice of extinction monitor detector appears robust and self-calibrating, though it is a rare event experiment in itself with regards to backgrounds.
- There was no alternative plan to the AC dipole presented.

Recommendations

None

2.5 External Beamline

Findings

- A complete beamline that satisfies all the requirements of the beam delivery was presented. The required functions accomplished are extraction, momentum collimation, an AC dipole insertion, and final focus delivery to the target.

Comments

- Final focus was designed to accommodate reverse production solenoid operation. This type of operation is not in the requirement documents.
- No particle tracking simulations from extraction to target have been done.

Recommendations

8. Perform value engineering to reduce complexity, cost, and length of the beamline for the CD-1 review.

3.0 Accelerator II

Lead: Nancy Grossman

Contributors: Salman Tariq, Andy Stefanik, Wayne Schmitt

3.1 Production Target

Findings

- The project has suffered from a lack of engineering support in this area, and just recently contracted the services of outside and FNAL engineers.
- The beam size is 1mm (rms) with target positional stability requirement of <0.4 mm and alignment requirement of <0.5 mm.
- The design team responded to the recommendations from the December 6, 2011 review.
- The total heat load for the current target design is estimated at ~2.15 kW (based on MARS). The power distribution is rotationally symmetric but varies longitudinally where it rises for the first 2 cm and then decreases linearly till the end.
- A radiation-cooled target is mechanically unstable and thus not feasible; an active rather than passive cooling system has therefore been adopted.
- The current production target is a water cooled gold rod (3 mm radius x 16 cm long) encased and positioned inside a titanium jacket by 3 longitudinal vanes. The original MECO design mounted the target within the solenoid via 2 titanium supply and return lines. This design was recently replaced by a spoked “bicycle wheel” target design that offers greater stiffness and positional stability without significantly affecting stopped muon yield. The alternate “bicycle wheel” is the new baseline design.
- Following the recommendation from the internal design review, the heat load scaling factor was reduced to 1.5x. As a result, RAL engineers have recommended reducing the flow rate from 1.0 to 0.5 gpm which significantly reduces the pressure drop across the target (by more than 3x). However, there is a concern that this can lead to a dramatic increase in temperature since the flow falls within the lower limit of turbulence.
- Details on the manufacture and assembly of the target and support system were not presented, such as the weld details showing coupling of all the components (e.g. “bicycle wheel” assembly and its attachment to the target assembly).

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- Integration and mounting of the target to the heat and radiation shield is critical, yet the design is at a very preliminary stage. Alignment details have yet to be worked out.
- A conceptual target remote handling scheme has been developed and was presented.
- The production target will have a separate RAW system.
- Conceptual design work of the removable upstream window needed for target change outs with cooling line feed-through has not been done.
- It is possible to steer the beam into the target cooling lines, but this is not cause for great concern since the cooling lines are very thin and well cooled. The anticipated energy deposition is $<10W$ and there are no stress wave concerns. This study is ongoing.

Comments

- We commend the project for securing extra engineering help, particularly the High Power Target expertise of the RAL group. Significant progress has been made towards the conceptual design, but significant work still remains to be done. Going forward, the project should continue with plans to utilize the resources of RAL engineer's through the preliminary and final design.
- The safety factor being presented is not a true safety factor in the engineering sense, meaning it is not based off of allowable stresses, temperature limits, etc. It is simply multiplying the target heat load (from MARS) by a scaling factor to reflect the uncertainty or error in the MARS prediction. Actual (engineering) safety factors should be determined from thermal and stress analysis of the target and support assembly.
- Cost implications of the remote handling procedure/facility can be significant and project management should be aware of that. This design needs to be significantly advanced early on since it has implications on civil construction and component design. We suggest conducting value engineering to explore different target replacement options and then focusing in on one design concept.
- The production target technical and physics requirements have been laid out; however target alignment requirements (particularly the interface with heat and radiation shield and the production solenoid) were not clearly stated. Maintaining proper beam position on target is critical and considered a risk item, therefore creating a detailed alignment plan should be high on the priority list.
- Active (liquid) cooling introduces added complications of a raw cooling system, plus the possibility of leaks that could have potentially detrimental consequences. Careful thought should be given to all connections and their potential to fail

(either by fatigue or other means). Details of a target water leak detection and containment system were not available or presented and should be developed.

- We agree that the production target is a high risk device that requires a thorough risk-failure analysis; however we did not see evidence of this analysis although it might exist. This analysis should be developed and included in the CDR.
- Radiation damage, radiation induced corrosion, and erosion of target materials is not well understood and a possible risk. Continue to investigate radiation effects on materials exposed to proton beam. Consider expediting the erosion tests on gold target proposed by RAL and continue to explore other target material options.
- The CDR includes limited information on the work done by RAL thus far; suggest adding more details on thermal and stress analysis, remote handling, etc. before the CD1 review.
- Handling and storage of failed targets was not presented, nor was a design for a transport coffin. The crane capacity should be able to handle the combined load of a target plus coffin.
- Most of the recommendations from the internal design review have been addressed, such as ramifications of an off center beam on target. However, certain areas still need to be addressed, such as analysis of the end windows and alignment stability.

Recommendations

9. 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 CD1 review.

3.2 Heat Shield

Findings

- The requirements document is started. It is titled “Requirements for the Mu2e Production Solenoid Heat and Radiation Shield, HRS.”
- There are generic interface requirements for the HRS in the following interface documents: Accelerator Interfaces, Muon Beamline Interfaces, and Solenoid Interfaces. There is no specific interface document for the HRS.
- The design team responded to the recommendations from the December 6, 2011 review.
- Current design for the HRS was presented.
- Heat generated in the HRS was determined in MARS15 simulation.
- The design consists of four, high-silicon bronze sections and three tungsten alloy sections. The sections bolt together. Belleville washers will be added to the design if needed to accommodate thermal expansion. The assembly plan was illustrated.
- HRS material choice comparison was presented.
- Current design concepts for the transport frame and fixture were presented.
- The installation plan was illustrated.
- As discussed in the presentation, one of the biggest technical risks is lack of thermal conductivity between the sections of the HRS with the most energy deposition and the water cooling tubes.
- The design team has not yet investigated the effect of accidentally steering the beam into the HRS.
- The design team has not yet assessed HRS heating during a quench of the production solenoid or the transport solenoid.

Comments

- The requirements document is in good shape for the current design.
- It might be good to start an interface document for the HRS to record specific requirements, like the specific value for the “acceptable outgassing rate” mentioned in the presentation, and details worked out verbally, like the rails between the HRS and the production solenoid, and beam entrance port details. This will save searching through multiple interface documents.

- Written responses were provided for all of the recommendations from the December 6, 2011 review except for the one about moving the water cooling manifold outside of the vacuum vessel. This recommendation was discussed during the presentation. The response should be added to the written responses to close that that set of recommendations.
- Much design work has been accomplished since the December 6, 2011 review. The design team is still working out details but the design is ready for CD-1.
- Transferring heat from the HRS to the water cooling tubes was discussed in depth during the presentation. The project team needs to prove that metal-loaded grease is a viable thermal interface material in a radiation environment. The design team continues to work on this very critical detail. They are also considering alternative details to ensure reliable heat transfer, such as brazed copper tubing in channels.
- All of the effects of accidentally steering the beam into the HRS must be determined. Two effects in particular are local radiation dose to the production solenoid and boiling of the cooling water.
- Eddy currents generated in the HRS during a production solenoid quench or a transport solenoid quench will heat the HRS to varying degrees. Two of the questions to answer are will the cooling water boil and how will the water cooling system handle the vapor if the water does boil?

Recommendations

10. Determine all of the effects of accidentally steering the beam into the HRS.
11. Determine all of the effects of eddy current heating in the HRS during a quench of the production solenoid or of the transport solenoid.

3.3 Proton Beam Absorber

Findings

- The requirements document is started.
- There are generic interface requirements for the absorber in the Accelerator Interfaces document. There is no specific interface document for the absorber.
- The design team responded to the recommendations from the December 6, 2011 review.
- Design requirements were summarized in the presentation.
- Current design for the proton beam absorber was presented.
- Heat generated in the proton absorber was determined in MARS15 simulation.
- The current design consists of a 1.5 x 1.5 x 2 m aluminum core encased in 3.5 x 3.5 x 5 m concrete structure.
- The absorber must be able to accept the entire beam power in the event that the target is missed, or during pre-targeting beam tests. In addition, it must be able to accept possible increases in average beam power as set by the Mu2e Proton Beam Requirements Document, presently set to 32 kW (25 Tp/s at 8 GeV kinetic energy).
- An aluminum absorber with two active water cooling circuits is selected due to the uncertainties of characterizing passive conductive or convective paths out of the structure, and the large heat depositions in the accident case.
- Finite element temperature distribution plots were presented for the accident condition. One with passive air cooling and one with air cooling.
- Residual activation on contact at the beam absorber wall was presented.

Comments

- Assumptions for losses for calculating groundwater, surface water and soil activation appear reasonable. Calculations for catastrophic RAW system loss are not yet calculated, but should not be an issue.
- It might be good to start an interface document for the absorber to record specific requirements, like the water connections.
- Written responses were provided for all of the recommendations from the December 6, 2011 review except for the one about developing a plan to recover from a water leak.

- The design team needs to describe the heat transfer path from the aluminum to the cooling water. In particular, if tubes are inserted in the aluminum or concrete the team needs to prove the thermal interface between the outside diameter of the cooling tube and the absorber will survive in the radiation environment.
- One of the recommendations from the December 6, 2010 review was “Re-evaluate the accident condition assumption assuming an interlocked monitoring system. Then, if results are favorable, consider passive air cooling the absorber”. The response from the project team was “We have not had the engineering resources to consider passive air-cooling combined with a beam interlock system to protect from the “accident” condition. (The “accident” condition being when the beam misses the target and dumps more than normal energy in the proton absorber.) It remains an alternative to be evaluated". We encourage the design team to evaluate this alternative proposal because it can potentially eliminate the need for water cooling.
- The design is ready for CD-1.

Recommendations

12. Re-evaluate the accident condition assumption assuming an interlocked monitoring system. Then, if results are favorable, consider passive air cooling the absorber.
13. Develop a conceptual plan to recover from a water leak.

3.4 Radiation Shielding

Findings

- Since the AP Ring Service Buildings will be a major source of air-scattered radiation (“sky shine”) in public areas near Wilson Hall and other public areas on site, a detailed plan to add or retrofit shielding is needed. Although much work has been done to quantify the problem, a viable solution does not yet exist. Two possible solutions are being investigated, both of which also require an electronic berm. The Project is seeking a solution based upon normal losses of up to 1% of full beam power distributed over each service building, not to exceed 2% for all three service buildings. The basis for this is that all beam transfer points will be shielded with supplemental shielding and unspecified additional losses at these levels are not possible.
- An electronic berm is a cornerstone of the present radiation safety plan. Using an electronic berm (e-berm), the project states that the maximum beam loss will be limited to about 2% of full beam power in the AP1, AP3, Accumulator Ring, and A/D transfer line. An e-berm has a device at the start and end of a region to measure total beam, compares the two to determine losses and, at a given level, trips the beam. When used for personnel or environmental protection, as with Mu2e, it is required to be approved as redundant, fail-safe, calibrated and have a heartbeat.

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- An electronic berm will not help set a limit of losses in the Debuncher Ring. The project expects to have 2 to 5% normal beam loss under the AP30 service building at the Debuncher extraction region which will require a significant shield design effort. A method to detect and mitigate prolonged beam loss in the remainder of the Debuncher remains to be determined. If suitable safety-grade, radiation long counters can be developed and provided by the lab, these could be deployed in the rings and would limit the duration of excessive beam loss. Safety pedigree requires failsafe, heartbeat, calibrated, and redundant.
- Collimation systems can be used to fix losses at designated locations
- Groundwater, surface water, soil and air activation calculations have been performed. Ground water and surface water radionuclide contamination is not beyond current routine levels seen at the laboratory. No special considerations or additional shielding is needed.
- Air activation from all the sources is a significant fraction of the lab's emissions budget, but can be mitigated with proper design of the ventilation and air flow management.
- The production solenoid heat and radiation shield, absorber and target RAW system designs are generally typical of other systems at the lab, have secondary containment integrated as part of the water skids, and do not appear to present significant concerns. They have some flexibility to accommodate more load. Responsibilities and interfaces are well-defined, though not in a formal interface document.
- The detector hall will include a work cell with remote manipulation. Although a primary target design has yet to be finalized, the work cell will be required for servicing various highly radioactive components.
- The project supplied responses to many to of the radiation safety recommendations from the "Report from the Mu2e Radiation Safety and Target Station Review held Dec 6, 2010". Those that were not addressed or carried over into the recommendations in this report, but that must still be pursued further are:
 1. Develop plan for isolated water drainage system using radiation protection and civil construction subject matter experts.
 2. Critical systems and components whose failure would have catastrophic consequences for the experiment should be identified and risk of failure mitigated appropriately. Those items that cannot be mitigated adequately should be planned to be replaceable.
 3. Tritium buildup in the cryogenics helium should be evaluated. This is needed to evaluate annual tritium releases based on the number of quenches.

- Radioactivity build up in the target and possibly absorber cooling water should be estimated. (done) Shielding of these cooling system and disposal of the activated water and DI-bottles containing radioactivity should also be considered, in the design of the facility.

Comments

- Assumptions for losses for calculating groundwater, surface water and soil activation appear reasonable. Calculations for catastrophic RAW system loss are not yet calculated, but should not be an issue.
- The use of radiation long counters could be a value engineering effort, if determined feasible, for Mu2e and other future projects at Fermilab. In lieu of long loss monitors, many interlocked radiation detectors would be needed, far above the number presently available at the lab. Setting up a lab project of developing a prototype long loss monitor for future projects, preferably on the timescale of use for Mu2e would be very beneficial.
- Roles and responsibilities of project ES&H personnel are not well established. Currently, resources from AD, PPD, and the ES&H Section are utilized, however the project could benefit from a dedicated person to coordinate these efforts and make sure all areas are appropriately covered.
- If neither of the present sky shine solutions proves to be viable, the project has a serious problem.
- Solutions to several radiation safety problems, such as radiation sky shine from sources at the P-bar service buildings, depends upon the laboratory's desire and ability to implement an 'electronic berm' system. This effort is needed for several future projects, not just Mu2e. The project needs to develop a 'fall-back' plan (e.g., additional interlocked detectors, reduced beam intensity, more shielding) in the event this effort does not occur in the time frame needed for the experiment.
- A more detailed knowledge of beam loss scenarios, accident and normal, would provide a better basis for shielding estimates and mitigation techniques and value engineering. Solutions for likely beam losses at some transfer points, such as from slow resonant extraction in the Debuncher have not been investigated in any detail. Since these may complicate solutions to other radiation control problems, a better understanding of this is needed, particularly in the high loss area of the resonant extraction region where beam design is just getting to the point to allow radiation studies.
- The Production Solenoid target residual activity has been modeled at $\sim 2.6E7$ mSv/hr (1 yr running, 7 days cooldown). Although a system for remote manipulation has been designed, this level of expected activation has not been seen before at Fermilab and unique ALARA control measures may be needed. Also, radiation damage issues due to such large dose rates do not appear to be well developed.

Recommendations

14. Assign a dedicated ES&H person to the project, who resides in the project office box, to coordinate ES&H issues project-wide and ensure all issues are being addressed appropriately, by CD-1.
15. Determine a viable sky shine shielding solution by CD-1.
16. Add the issue of successfully designing, building, testing and approving of the e-berm in the risk registry by CD-1.
17. Determine back-up plans for any areas that presently require an e-berm by CD-1.
18. The lab needs to form a committee to address the feasibility of an e-berm for Mu2e by CD-1.
19. If feasible, the lab needs to construct a “prototype” e-berm on a reasonable time scale for Mu2e.
20. More accurately determine losses (points and amounts) in both rings and the transport lines.
21. Put more resources on the beamline design of the resonant extraction area so that shielding designs can proceed in this area.

4.0 Conventional Construction

Lead: Jesse Adams

Contributor: Elaine McCluskey

4.1 Architectural

Findings

- An architectural conceptual design has been developed and was presented for each of the proposed structures.
- Conceptual design included initial rendering, floor plans and sections.
- The review sub-committee was informed that the architectural design meets Fermilab's Architectural Guidelines and has been initially approved by Project and Lab management.

Comments

- Team has made adequate progress for this level of review.
- The architectural design is adequate and appropriate for the proposed operation and function of the facility.
- There were no technical or constructability issues found.

Recommendations

None

4.2 Site/ Civil/ Structural

Findings

- Drawings, Site Plans, 3-D images and sections were provided. In addition to sketches and 3D images, a total of 5 Civil drawings and 13 Structural drawings were provided.
- The site civil work presented included: re-routing an existing service road, site utilities, site parking and related service roads, fencing for radiation shielding and large earthwork to support the proposed new structures.
- Existing Soil Borings of areas adjacent to the facility exist and were provided. The team stated that additional boring will be conducted later in the design as required.
- Structural work includes the design of (5) unique systems:
- Mu2e Beamline Enclosure – Underground concrete beamline enclosure with approximately 21 feet of earth above to be used as shielding. Basic structure described was a concrete box-like structure with egress stairways along the length of the tunnel. For construction a large excavation and fill will be required. Work also includes minor structural modifications where the proposed beamline is connected to the P-Bar beamline.
- Detector Service Building and Detector Enclosure – Complete new facility with a sub-terrain level to be used to house the majority of the experiment equipment. Structure described was a basic conventional facility with a concrete foundation and sub terrain level with steel frame for the above ground structure.
- Cryogenic Support Building – Small structure, with limited to no complexities.
- MI-52 Service Building Addition - Small addition to an existing facility. Small structure, with limited to no complexities.
- Antiproton Shielding Upgrades – Due shielding requirements, the team has developed a design that encapsulates the existing facilities with a large mass of concrete on the top and sides of the building. An architectural element of a canted wall was presented.

Comments

- Team has made adequate progress for this level of review.
- The Site/ Civil/ Structural design is adequate and appropriate for the proposed operation and function of the facility.
- There were no technical or constructability issues found.

Recommendations

None

4.3 M/E/P

Findings

- Drawings, Process diagrams, Single lines and preliminary tables were provided.
- Preliminary loads (cooling and electric) were completed. The values are not finalized but team feels comfortable with the values. The values proposed were reportedly within the available capacity of proposed design and existing utilities.
- A preliminary fire/life safety study was conducted for the new construction to provide guidance on egress, fire suppression, alarm, and detection, which have been incorporated into the design. This design follows all codes and does not utilize an equivalency approach. The study did not include existing PBar facilities. The analysis did not include any special provisions for oxygen deficiency hazard (ODH), although an estimate of ventilation requirements for ODH was provided by the experiment until an ODH analysis is performed.

Comments

- Team has made adequate progress for this level of review.
- The MEP design is adequate and appropriate for the proposed operation and function of the facility.
- There were no technical or constructability issues found.
- Existing facilities that are being affected by this project may need to be upgraded to meet current life safety code provisions, including fire suppression, alarm, and detection.

Recommendations

22. Existing PBar facilities should be evaluated for fire/life safety code compliance.

4.4 LEED/Sustainability

Findings

- The project team has studied the LEED Certification requirements and ASHRAE considerations for the facility. A LEED assessment for the facility has been prepared, along with a listing of guiding principles and ASHRAE considerations prepared by outside consultant.
- The project review team was informed the project cannot feasibly meet the DOE requires to achieve LEED-Gold Certification due to the function and operation of the facility. Specifically, the facility will not be occupied on a regular basis. Out of the possible 37 points achievable for the facility, the team has indentified 26 possible points.
- In lieu of LEED-Gold Certification, the project will utilize guiding principles and ASHRAE recommendations to meet sustainability goals.
- The project team has not received and is not intending to seek a formal waiver or notice from the DOE as to the LEED-Gold exemption.

Comments

- The team explained very well the reasoning for the LEED certification issues.
- The proposed guiding principles are well developed and a good alternative to LEED certification for meeting the projects sustainability goals.
- Formally communicate the project's objectives relating to sustainability to DOE Site Office/ Federal Project Director.

Recommendations

None

4.5 NEPA

Findings

- The project is pursuing a Categorical Exclusion (CX) under the premise that at least one exception stated in CFR is applicable to the project. If the CX is not approved, an Environmental Assessment (EA) will be required.
- A draft wetland assessment has been prepared and was provided by the project team. Additionally, a wetland report prepared by an outside consultant was prepared and provided for review.
- At least one wetland like area may be disturbed by the project. The project team members have stated the Army Corp. of Engineers will be making a determination as to the status of the potentially disturbed wetlands in late May.

Comments

- The team is making the appropriate amount of progress required for a CD-1 review.
- The approach and strategy for the targeted CX is appropriate and reasonable for the nature of the project.
- The project team should consider the schedule and cost risks associated with the possible need for an EA.

Recommendations

None

4.6 Risk

Findings

- The team has established and developed a preliminary risk register.
- Only non-quantitative risk information was provided

Comments

- The team is making the appropriate amount of progress required for a CD-1 review. Further development of the risk register should be implemented as the project progresses and risks/opportunities are identified.
- In conjunction with the efforts to determine a preliminary “rolled-up” estimate, the team should start to quantify risk to determine approximate levels of contingency.

Recommendations

None

4.7 General

Findings

- FESS/Engineering has produced a conceptual design for the Mu2e facility through iterative processes of meetings and discussions. Documentation for this design includes a draft requirements document, an interface specification, and 39 drawings. The requirements and interface documents have not had sign-off in the Mu2e Docdb, and have several placeholders where information is lacking.
- The design has been developed by FESS/Engineering staff under the leadership of the L2 manager for conventional construction with some life safety, structural, and cost estimating assistance from architect/engineer consultants. Post CD-1, the L2 manager will continue to have responsibility for the design and construction of the conventional facilities, and intends to have a subcontract in place for a consultant architect/engineer for preliminary (and then final) design.
- Although the Project Manager stated the g-2 experiment would be accommodated by Mu2e planning, the conventional facilities design has not yet taken this into account. Two possible g-2 layouts were presented, both of which would have impact on the conventional facilities. No direction has been provided to the conventional facilities team on this issue.
- Some of the conventional facilities systems include several design alternatives, e.g., varying cooling and mechanical loads for the same equipment, due to uncertainties from the technical systems.
- The project has not yet rolled up the costs to see if they are within the cost range. When this is done, it could result in additional value management and design revisions that would affect the conceptual design presented for this review.
- Several alternates have been explored in getting to the current design. Two siting alternates were developed and documented in Project Definition Reports in 2008 and 2009, but subsequently superseded by the current design due to physics requirements.
- Some alternatives are still being studied as part of value management, and may remain unresolved until after CD-1. Major facility systems alternates under consideration at this time include using pond cooling in lieu of dedicated cooling towers, providing capacitors on electrical equipment, using alternative shielding materials at the PBar Buildings, reuse of existing Tevatron 1500 KVA transformers in lieu of new purchases, upgrading the existing LCW plant at CUB in lieu of new construction, using existing shielding steel and blocks in lieu of new purchases, and finding ways to utilize excavated fill near the project site to avoid trucking and disposal.

Comments

- The conceptual design is well advanced, is more than adequate for a CD-1 review, and appears to meet the requirements from the scientific users.
- The organization and management lines are clear and centered in Tom Lackowski as L2 manager. This strategy has been successfully used on similar FESS projects in the past.
- The conceptual design requirements and interfaces have been developed more through meetings and conversation than through documentation. Nevertheless, the requirements and interfaces need to be documented and signed off by all affected L2 managers in order to provide assurances that the design meets the requirements of the experiment. This an ongoing process, with higher level requirements documented for CD-1, and more detailed requirements updated as the design progresses. The conceptual design is documented in the CDR very completely, and could provide a foundation for the request for proposal for the preliminary design with a consulting architect/engineer.
- A single reference design for conventional facilities at CD-1, accompanied by alternates, would provide a clear basis for costing and comparisons.
- Accommodation of the g-2 experiment needs to be incorporated into the conventional facility planning now, as it affects civil/structural as well as utility planning that would need to be revised in the future, and so that it can be shown in the design for CD-1.
- It's likely that after rolling up costs, at least one iteration of the design will be necessary to meet cost targets, which will take time and could impact the schedule for future CD-1 reviews.
- The conventional facilities team has developed a good list of value management alternates for further consideration as they continue to try to reduce capital and life-cycle costs.

Recommendations (See also: Detailed Recommendations Supplement)

23. Consolidate the conceptual design into one reference design to provide clarity, with alternates for either scope contingency or to help provide a cost range.
24. The Project Manager should provide direction to the conventional facilities on what level of accommodation should be provided for the g-2 experiment as soon as possible to incorporate this into the conceptual design.
25. The project should understand as soon as possible if iterations on the conceptual design are required due to cost constraints, in order to allow sufficient time for coordination between subprojects and to produce a revised design.

Closeout Presentation

26. Requirements and interface documents should be completed at a high level with sign-offs.

5.0 Solenoids

Lead: Jim Kerby

Contributors: Alain Herve, Pasquale Fabricatore, Joel Fuerst, Herman Ten Kate, Akira Yamamoto

Findings

- The solenoid system has a set of signed requirement documents specifying the field quality along the muon path. Some approved interface documents also exist. Several other draft documents were also made available to the committee. To large extent these high level requirements have been used for the conceptual design.
- The design as presented and documented is consistent with a Conceptual Design, and can meet the requirements as stated. The committee is convinced the solenoid system is feasible, can be built and operated reliably provided a proper detailed design is executed, qualified vendors are used, and rigorous quality control implemented.
- Considerable optimization of the design, consistent with the CD-1 to CD-2 stage, is needed. Given that the solenoid system is a long lead item for mu2e, completion of all of these optimizations in time for CD-2/CD-3a will be a priority for the collaboration.
- Design conditions, including transportation and failure modes, are not completely documented.
- Modeling of the sensitivity of the physics performance as a function of reduced magnet performance has been started. This will provide important input to the necessary final design features, and acceptance tests and measurements such that a successful physics experiment can be run in case the solenoids are running off the nominal design point.
- Three parallel circuits for TS (TS1-2, TS3, TS4-5) are proposed as a requirement from the physics experiment. However, the necessity of this arrangement was not clear to the reviewers.
- A comprehensive plan of magnetic mapping of each section of the system was presented using state of the art positioning and measuring systems.
- The general installation scenario is credible and supported by examples.

Comments

- The conductor design and procurement will drive the schedule completion of this development and the associated qualification tests, including winding trials should

be the highest priority of the collaboration. If it is useful ATLAS central solenoid coil winding samples can be supplied.

- In light of the unusual requirements of the production solenoid, a more robust optimization of the coil design accounting for all system requirements should be done. For starters we suggest increasing the operating margin, thinning the Al-stabilized conductor (to 6mm?), and increasing the number of coil turns. In addition several parameters should be more completely developed: the RRR v. yield strength of the production solenoid conductor, the heat transfer v. the electrical insulation design, and the coil design and winding technique given the ratio of the coil radius to conductor thickness.
- The critical current densities assumed by the collaboration for PS generated considerable discussion within the committee. Increasing this value goes in the right direction to increase the design margin, however, the value used by the collaboration in the design should be well documented.
- The cooling/operating margin for all of the coils needs to be carefully ‘guarded’, in the context of the complete cryogenic system. The production solenoid design margin should be increased given the special operating requirements and uncertainty in energy deposition in that magnet.
- The magnet heat load analyses should use the same “4.5K” and shield temperatures as supplied by the cryo system.
- Review the peak allowable voltage, and consider whether a lower voltage of 600V could be acceptable. The test requirements for a design voltage of 1kV to ground are strenuous and restrict procurement sources.
- Develop complete temperature margin plots for each coil, in the nominal operating and worst case scenarios.
- The design and fabrication of the transport solenoid coil support system results in a maximum coil motion during excitation of 80 microns. This is a source of magnet training. The design should be revisited to fix this.
- The DS has a sufficiently low E/M ratio (~2kJ/kg) that some optimization might be possible. Many magnets operate with a value more like 5kJ/kg. A review of the conductor design to minimize the conductor variation, and to optimize the Al stabilizer fraction, may yield some cost benefits. Considering conductor both horizontal and vertical orientations may be fruitful. The use of a single layer coil section in the DS should be considered as well as, or in combination with splitting the DS in two sections for reasons of cost and risk. The field distortion by the return bus in the single layer option can be solved by using 2, 4, or 6 parallel return busses equally distributed around the coil circumference.

- A design constraint on the magnet systems includes the time constant of all systems being very close to the same. Reconsideration of whether this constraint is required may simplify the design of the individual magnets.
- The production solenoid cable stability should be looked at to understand the minimum RRR @5T that can be accepted.
- We would not recommend gluing the end flanges to the coil proper, this interface will be prone to cracks.
- The maximum allowable stress on the epoxy should be documented.
- The engineering design effort at the vendors will have to be carefully contracted and monitored to avoid a second iteration of this process.
- The integration of the production solenoid with the construction mandrel should be determined. Experience from other collaborations, and the RFI response from the vendors should be utilized to make this decision, and the design updated to reflect this.
- The design of the cooling scenario internal to the production solenoid coil should be carefully reviewed, accounting for the additional risk introduced to the electrical safety of the system.
- A dielectric film should be considered for inclusion in the conductor and ground insulation, particularly in the PS winding pack and around the TS packs.
- The interface with the primary beam and the primary target handling and radiation protection inside the Production Solenoid needs to be better documented.
- The baseline mechanical designs of the solenoid cryostats and supports appear sound and conservative. Given the difficulty of access, they should be reviewed for failure scenarios where one of the supports / tie bars breaks and increased redundancy considered.
- The safety factors of all mechanical support systems should be clearly and consistently presented.
- The conceptual design of the cryostat vacuum system should be documented.
- On the production solenoid cryostat supports, introduction of a discrete intercept piece on the tie bars will help define the thermal intercept.
- The pre-load scenario for the DS supports should be documented.
- The conceptual cryogenic system includes the consideration of thermosiphons for cryostat cooling as compared to forced flow. There is considerable experience

with thermosiphon cooling on other solenoids, the collaboration should utilize this experience and apply this technique if possible. The committee members with experience volunteer to be contacts for further information if desired.

- As presented there appears a good case to use forced flow cooling for the TS and thermosiphons for the PS and DS, and in particular the PS to improve the temperature margin and because the heat generation is varying along the length of the PS solenoid. However, the feasibility using thermosiphon cooling must be assessed taking into account the real implantation of feed boxes and magnets and the necessary radial space must be provided inside each cryostat
- The conceptual cryogenic design includes five feedboxes, one each for the transport and detector solenoids and three for the transport solenoid. These are in response to the desire for the separate acceptance testing in the hall and the requirement for quick access to the TS3 segment. The committee strongly believes series powering of the magnets should be explored, and the number of feed boxes reduced, to the fullest extent.
- The cryogenic system addresses the steady state loads adequately; a better understanding of the cooldown, warmup, and recovery time requirements needs to be developed.
- The superconducting bus between the magnets and the feed boxes needs to be carefully designed, and incorporated into the electrical, protection and cryogenic system designs.
- A more complete quench protection scheme, including the buswork, is needed. Quench back effects between the modules must be studied.
- The mutually coupled coil circuit in series operation should be normally taken in order to minimize mutual coupling effect including unbalanced mechanical forces during excitation. We advise to investigate the series operation with a single loop circuit for the TS operation.
- A fast dump of the system appears to require two days to re-cool the cold mass. Could a helium reserve be foreseen such that this could be better optimized.
- Putting a diode in series with the dump resistor can be considered.
- The conceptual design of the controls system should be documented.
- Value engineering on the components of the cryogenic system, for instance the reuse of Tevatron leads, the satellite refrigerators, and the cooling methods is underway and supported by the committee. Though well maintained the 25-year old equipment may not be the most economical solution. Capacity of the satellite refrigeration system routinely achieved should be confirmed.

- A brief discussion of the magnet iron was presented, but includes a good conceptual design that is supported by the committee.
- The very extensive program of magnetic measurements should be incremented to include measurements of the magnetic field at reduced fields, as contingency for future 'reduced operating point' scenarios as suggested by the physics studies.
- The extensive field mapping does not dispense with the need to assemble all the coils correctly on the theoretical axis. Initial alignment studies, and mechanical studies of motion with cooldown and excitation suggest a final solution is achievable. However, to ease the difficulty the suspension systems should be designed to prevent radially outward motions of the cold masses during cool down and excitation and a full fiducialization of the cold mass to the cryostat should be included in the design.
- Ensuring that the sub-detectors are non-magnetic and do not modify the field map should be done through QC procedures and electrical tests outside of the DS.

Recommendations

27. Finalization of the conductor design, qualification tests, and subsequent procurement should be the highest priority of the solenoid effort.
28. The physics simulation effort studying operation off the design point must continue at a high priority. Results of these simulations will provide important input to the magnet design margin, the system design to include features to run off the design point, and acceptance test planning.
29. Redesign the magnet systems using a lower and more typical value for the peak voltage of 600V.
30. The 1.5K temperature margin for the solenoids should be documented and closely guarded at this phase of the project. The margin on the production solenoid should be increased.
31. A complete R&D plan needs to be developed to answer open questions in a timely manner. Coordination with CERN and KEK efforts may help accelerate the program.

6.0 Muon Channel

Lead: Joe Howell

Contributors: Peter Limon, Rich Andrews

6.1 General

Findings

- The subcommittee is convinced that the Muon Beamline technical design is presently at a stage of design that could succeed at a conceptual design review, even though there are a number of details that are not yet filled in.
- It was the subcommittee's impression that the simulations necessary for the design of many components of the Muon Beamline systems was not sufficiently advanced to give timely design guidance. Examples: neutron background originating at the PS (Muon Beamline shielding); detailed design of the collimators; assembly sequence of the Muon Beamline magnet; radio-activation levels (repair time)
- It was the subcommittee's impression that there are some areas where communication among Muon Beamline systems and other systems of Mu2e was less than robust. Examples include pin-out requirements for the calorimeter and tracker; assembly sequence of the transport solenoid; design of the access and egress for maintenance of the TS3.

Comments

- Now is the time to begin the detailed designs of beamline components. These designs rely on results from simulations. The results are often in place but not always available in a timely fashion.
- Now is the time to establish the integration and configuration control effort.

Recommendations

32. Increase the overall simulation effort for the experiment.
33. Dedicate a significant portion of the simulation effort to the Muon Beamline (as its primary responsibility).
34. Augment the project engineering office manpower in the timeframe of CD1 to address the project wide integration and interface issues.

6.2 Vacuum System (wbs 5.2)

Findings

- Muon Beamline is responsible for the experiment vacuum system. A requirement was established at $P < 10^{-4}$ torr. The major issue is the large gas load from the large amount of plastics, the tracking chamber and virtual leaks.

Comments

- It was the subcommittee's impression that there is a significant mismatch between the performance of the upstream vacuum system and the downstream system. The upstream system reaches its operating pressure in 45 minutes, while it takes the downstream system 10 hours. It certainly seems that the upstream system is overdesigned. On the other hand, we do not believe that the virtual leaks presented by the many blocks of radiation shield were taken seriously enough in the calculation.
- The outgassing and leak rates for the tracking system should be investigated by assembling sections of the tracker and subjecting them to tests and accelerated life tests in a vacuum chamber. The life tests should include cycling, temperature fluctuations and other aging processes.
- The experiment should at least consider the possibility of a skin over the PS radiation shield to eliminate the issue of virtual leaks.

Recommendations

35. Establish an R&D plan by the CD1 review to determine the leak rate and reliability of the tracker gas system under operational conditions.

6.3 Collimators (wbs 5.3)

Findings

- There are three collimators. The central one is split into two pieces that have to be rotatable at least 180 degrees for beam sign selection, and has a thin window in between the two pieces that separates the upstream and downstream vacuum and removes P-bars from the beam. COL-1 may need to have additional internal shielding to decrease heating of the TS coil in that area. The material and inner bore shape of COL-5 has not yet been settled.

Comments

- The rotating collimator and the window to make COL3a & 3b is complicated, but there appears to be no way to avoid the complication. It is necessary to provide access to this area of the TS to permit maintenance and repair. It was not clear to the committee whether sufficient interaction with the conventional construction group had taken place to come to agreement on whether that issue is on their list. The design of COL-5 is hampered by the lack of Muon Beamline simulations.

Recommendations

None

6.4 Muon Beamline Shielding (wbs 5.4)

Findings

- Throughout this presentation it became clear that development of this effort was limited by input from simulation. This was true for both internal and external shielding.
- Welding of the segmented vacuum tube is a shared responsibility: the requirements come from the vacuum group, but the welding for assembly of the tube is the responsibility of the cryostat WBS.
- When considering the maintenance of the collimator, there is a concern that consideration of space requirements (Confined Spaces) and ODH considerations has not been done.

Comments

- This element needs additional simulation to verify the shielding requirements.
- Solidify the interface between the cryostat and shielding to ensure the tube assembly created has welds of high vacuum integrity
- ODH and Confined Space considerations should be a part of the ES&H Requirements for this activity.

Recommendations

None

6.5 Stopping Target (wbs 5.5), Stopping Target Monitor (wbs 5.6), , Proton Absorber (wbs 5.7)

Findings

- The current design for the Stopping Target consists of 0.2 mm thick aluminum disks supported by tungsten wires.
- The current design for the Proton Absorbers consists of a 0.5 mm thick polyethylene sheet rolled into a cylindrical shape and supported by a lightweight structure, and by the tracker at the downstream end.
- The current plan for the Stopping Target Monitor is to use a commercial Ge detector with a cryo-cooler.

Comments

- The plans presented for investigating alternatives to the single polyethylene sheet and prototyping the support systems are reasonable.
- The selection of a commercial stopping target monitor solution with the planned radiation effects study is reasonable.

Recommendations

None

6.6 Muon Beam Stop (wbs 5.8), Neutron Shields (wbs 5.9)

Findings

- The current design of the Muon Beam Stop consists of concentric cylinders of polyethylene, stainless steel, and lead.
- The Neutron shield consists of 3 elements: an internal absorber made of polyethylene mounted inside the detector solenoid, an external absorber made of polyethylene plate mounted inside the iron yoke, and an end shield made of stainless steel.
- For fabrication reasons the cylindrical polyethylene portions of the Muon Beam Stop and Neutron Shields are constructed from stacked rings with 0.1 mm gaps between the rings to facilitate evacuation.
- The polyethylene surface of the Internal Neutron absorber is the largest surface area of any material inside the Detector Solenoid.

Comments

- The magnetic field in this portion of the detector solenoid may be low enough that the selection of 316L stainless steel for its lower magnetic permeability may not be justified. In fact, ss 316L is specified throughout the muon beamline design, which is often overkill.
- The current design borrows from the MECO design, which uses polyethylene as a primary material. The investigation of alternatives to polyethylene may be very beneficial to fabrication costs and vacuum performance.

Recommendations

None

6.7 Detector Support Structure (wbs 5.10), System Integration (wbs 5.11)

Findings

- The current design involves supporting the Stopping Target, Proton Absorber, Tracker, Calorimeter, and Muon Beam Stop from a set of rails that are mounted in the Detector Solenoid. All of the elements are connected and slide in and out as a unit.
- The design of the support rails creates gaps in the Neutron Shields where the rails are placed. The impact of these gaps on shielding effectiveness has not yet been simulated
- The alignment of each of the devices will involve a sequence of sliding the device into place, conducting a survey, and then sliding the device out for access to make alignment adjustments.
- A set of alignment tolerances have been established for each supported element and the initial placement and reproducibility tolerances that range from +/- 0.125 mm for the Tracker to +/- 2 mm for the Muon Beam Stop.

Comments

- The overall design is well developed and effective.
- The Stopping Target and Proton Absorber are passive elements and are unlikely to require maintenance. Installing the Stopping Target and Proton Absorber independently of the rest of the installed devices would appear to simplify the installation/removal operation.
- The design team presented reasonable workarounds if the gaps in the Neutron Shield present problems, but the simulation must be performed to determine if the additional complications to the design are justified.
- The cables and cooling lines of the tracker may apply loads to the tracker that affect its alignment and should be attached during the alignment process. The final alignment should be done after all cables are connected.
- The alignment tolerances are graded, but it appears that the alignment tolerances for the Beam Stop and Neutron Shield could be even larger.

Recommendations

None

7.0 Tracker

Lead: Peter Wilson

Contributors: Richard Kadel, Alan Hahn

Findings

- A conceptual design of the tracker was presented. The Tracker subproject provided documentation in the form of a Chapter 9 of the CDR, a requirements document, an interface document and several presentations by members of the tracker group. No supporting documentation beyond this level was presented to the committee.
- The tracker is the fundamental component of the Mu2e detector. Reconstructing the decay electron with high efficiency (acceptance >20%) and excellent momentum resolution (~180keV high side tail) for tracks momentum between 50 and 100 MeV is required to distinguish the conversion electrons from essentially all backgrounds.
- Physics requirements for the experiment have been translated into technical requirements for the tracker. The technical requirements have been explicitly translated into specifications for the tracker. For example, the tracker sits in a vacuum vessel that is required to be maintained at 10^{-4} torr. However, no budget was presented for the gas leak rate, out gassing from the tracker, or leaks from the cooling system.
- The T-Tracker reference design, , has ~20,000 straws oriented transverse to the field of the detector solenoid. Two alternate designs were also presented: a straw based tracker with tubes parallel to the field (L-Tracker) and an open cell drift chamber (I-Tracker). The L-Tracker design is no longer being pursued. The I-tracker continues to be developed as an alternate.
- Performance studies of the proposed design based on fast simulation indicate that it can meet the resolution requirements of the experiment. Optimization studies on configuration were shown demonstrating that the configuration has had a significant degree of optimization.
- The proton absorber represents the dominant mass traversed by the conversion electrons and is significantly larger than the mass traversed in the tracker. MC studies indicate it may not be needed with the proposed tracker design.
- The design of the tracker draws on prototyping and design experience for the proposed MECO, CKM and BTeV straw trackers. Initial prototyping work has used materials from the CKM prototyping work. A short term prototyping plan (pre-CD-1) was presented during the final breakout. A very preliminary plan for the CD-1 to CD-2 period was also presented.

Closeout Presentation

- The proposed readout electronics design is based on amplification and digitization (charge and time) inside the vacuum vessel. Data is transmitted out of the vacuum vessel via optical fibers. Digitizing inside the vessel reduces the number of vacuum feedthroughs by at least a factor of 10. The design is based primarily on commercial off the shelf components with the exception of the shaper and ADC, which are being implemented in an ASIC.
- Conceptual design of the infrastructure required to support the tracker has been carried at least through the vacuum interface. The initial low voltage power budget is 10kA at 2V. This is derived from DC to DC convertors just outside the vacuum vessel endplate. The LV power represents the majority of the vacuum feedthrough area for the tracker since a significant conductor cross section is required, and smaller interdigitated conductors for the supply and return current are needed to reduce the impact on the magnetic field to less than 0.1%. Total heat load from in cable dissipation is about 3kW.
- To minimize vacuum feedthroughs several design choices have been made, for example: digitization inside vacuum vessel, gas manifolds located on inside of vacuum vessel. The current plan for the tracker was not accurately reflected in the current design of the vessel endplate.

Comments

- Monte Carlo simulations of the tracker show that the number of stations has been simultaneously optimized to obtain the required resolution while reaching a plateau in tracking efficiency that does not improve with more planes. The mean number of hits on a track is adequate for pattern recognition and to reconstruct conversion electrons while the forecast number of misidentified hits on a track is very small. The straw technology allows the system to operate in a vacuum with the low mass needed to keep the multiple scattering contribution to the resolution within specifications. Additionally, the straws allow high rate performance and have a graceful approach to failure in that is essential in the almost inaccessible space that tracker occupies. The meantime between failures (MTBF) for the entire system of straws and their related electronics is defined to be greater than a year, although a detailed, bottoms up calculation of the MTBF is only at the most preliminary stage. The main outstanding issue is the rate of gas evolution into the vacuum space by the tubes, gas distribution and cooling lines or out-gassing of the components. This should be resolved by working prototype in a vacuum container where these affects or other unanticipated issues can be examined.
- The tracker section of the existing draft CDR is not at the CD 1 level. Much of the justification for design choices is not shown in this draft. However, the justification was shown in the oral presentations and in response to questions. Many of the figures in the CDR were obscure to the reviewers. The ones shown in the presentations were much clearer. Based on materials from the presentations, the CDR can be rewritten to the standard before the CD 1 review.
- The geometry of the tracker is justified at the level by MC studies.

- The need for time division not was demonstrated and is a topic for value engineering in the CD1 to CD 2 phase. This may have a significant impact on power and cooling required inside the vacuum vessel (as such has impact on vacuum feed-throughs).
- We did not see a plan for how to test the assembled detector prior to installation or how to do testing during maintenance periods. In particular, it was not explicit how testing will be accomplished when the detector transitions from operations inside a vacuum to maintenance operations at atmospheric pressure. In a related vein, a plan on how the detector will be tested prior to operations under vacuum should be developed.
- The R&D plan needs significantly more development. The plan needs to be tied to the significant risks for the detector design such as gas leaks into vacuum. There are many ways that the vacuum can be spoiled by the tracker: gas leaks, out gassing, or coolant leaks. The presented R&D plan focused primarily on the risk of leaking straws but we are at least as concerned about leaks from the manifolds.
- There is a need to make certain that the vacuum feed-through plan is in agreement between the Tracker and the vacuum vessel group. It is understood that this will likely change as the design matures. Keeping this interface between systems up to date will require constant attention.
- The heat dissipated in the LV power cables inside the vacuum vessel and the number of feedthroughs required to support them is a concern. The project should consider DC-DC conversion inside the vacuum vessel to reduce the cable plant. Need to understand how increase the MBTF to an unacceptable level. The LHC experiments are carrying out R&D on DC-DC conversion for the future tracker upgrades. These developments may be mature enough for use in Mu2e.
- Pulling the detector out for repair currently requires disconnecting at bulkhead. This could be painful for debugging problems. The collaboration should consider a moving cable tray to keep the detectors connected in the pulled out configuration. Fluids could be disconnected and reconnected using a second set of taps in the out position. A better understanding of the tradeoff between life time costs and operations should be undertaken.
- A plan was presented to limit the current in the straws induced by the beam flash every 1695nsec. If the straw system were to trip, or high ionization in the tubes causes them to break down, the experiment would be put in jeopardy. The ability of the straws to withstand a sudden large influx of particles needs to be verified in a test beam before CD2.
- The requirements document appears to be dated as it references what appears to be the I-tracker. It is not clear to the reviewers how these are being tracked.

Closeout Presentation

- The interfaces between the different groups seem to be understood, however the communication at these interfaces doesn't appear to be adequate to ensure a coordinated effort and design. It isn't clear whether this is the organization, or simply the lack of the manpower resources to handle these interfaces.
- We were presented org chart for both the entire Collaboration and for the Tracker, which went to Level 3. Three out of the five Tracker Level 3 Manager's names were listed. The missing L3's were for the Infrastructure and Detector Assembly and Installation. These missing level 3 subtasks were slated to be engineers. Unfortunately an Org Chart doesn't directly translate into engineering and technical resources, and there is a concern that the staffing levels here are not sufficient.
- We were told that there was configuration management, but didn't explicitly see it. As a result, we can't assess whether changes made will propagate out to the affected parties.

Recommendations

36. The Tracker section of the draft CDR should be updated prior the Director's CD-1 review, making sure that the figures are clear to people not related to the project and includes much of the MC work on optimization, hit counting and pattern recognition.
37. Prior to the CD-1 review a plan for the R&D to be carried out before CD-2 should be developed by the project. This plan should include operation of a prototype system *in vacuum*. The prototype system should be a reasonable approximation of a complete tracker panel (~100 straws) including manifolds and testing the survivability of the system in the environment equivalent to a beam flash.

8.0 Calorimeter, Cosmic Ray Veto

Lead: Jeff Nelson

Contributors: Julie Whitmore, Rainer Novotny

8.1 Calorimeter

Findings

- The collaboration has outlined the concept of homogeneous calorimeters with the main purposes of cleaning up the measured energy spectrum and aiding in identification of the 105 MeV conversion electrons. It is also possible that the calorimeter may have a role in trigger formation or in seeding track reconstruction. The reference deployment includes four radial vanes of calorimeter.
- They presented detailed reports based on two alternative scintillator materials including the reference design with LYSO:Ce and a back-up design based on PbWO₄.
- In either design the scintillation light is read out with a pair large area APDs attach to the crystal. A first scheme for signal amplification and digitalization were discussed. They also presented a concept for a flourinert-based energy calibration system with 6.1 MeV gamma rays from ¹⁶O, a light monitoring system and alternatives as photo sensors. The flourinert calibration is based on a closed loop system that was successfully used at the BaBar experiment.
- The collaboration presented beam tests with a small array with photons up to 300 MeV. An outline of the planned R&D program was forwarded to the committee during the review.
- At present, simulations for determining the calorimeter design requirements are not adequate to support the listed specifications. Background simulations (esp. from neutrons) were not completed at the time of this review.

Comments

- LYSO:Ce is presently still in the R&D phase with unsolved technical problems for effective mass production: inhomogeneity of light emission in large crystals due to Ce³⁺-distribution, self-absorption of scintillation light etc. Due to the strong statistical fluctuations of the shower at 100 MeV, non-linearities limit the energy resolution.
- The resources of the Mu2e calorimeter group at present do not allow for multiple R&D fronts of different calorimeter materials. The R&D for LYSO:Ce is much more challenging and the effort should be focused there. More beam tests for LYSO:Ce sub-arrays are necessary in order to fully understand the measured energy resolutions from recent beam tests. The calorimeter R&D plan should

include a beam test of a large scale demonstrator array to be operated in a 1T magnetic field (preferably in vacuum) in order to prove that the required resolution can be achieved. Because PbWO₄ calorimetry is well understood, the collaboration can rely on the experience of other experiments (e.g. PANDA-EMC and CMS) for their alternate design without requiring significant independent R&D.

- In-situ absolute calibration with low energy gamma rays fits well to the shower characteristics of 105 MeV electrons. LYSO:Ce has an intrinsic radioactivity (several transitions in the keV range) due to the (¹⁷⁶Lu). If it is practical the collaboration should aim to take advantage of these transitions for a second low energy calibration point as well as using the reference from energy deposition of cosmic muons.
- Light monitoring systems with at least two wavelengths should be considered to check changes of the crystal transmittance at the emission wavelength of 400nm (blue light) and the APD performance by green light.
- Previous experience with crystal procurement for other experiments has shown that it is beneficial to work with multiple vendors in order to keep costs down. Collaborators have worked with two vendors to this point. This should be maintained or even expanded.
- The recent addition of the group at Caltech provides significant additional support for the LYSO:Ce development and optimization due to their long experience in calorimetry with inorganic scintillators.
- Due to the lack of large area SiPMs, APDs with a minimized nuclear counter effect are presently the optimum photo sensor. However, the temperature sensitivity of the APD has to be considered either by thermal stabilization or the approach of a compensating pre-amplifier design as developed for the Crystal-Barrel Experiment at ELSA (Bonn, Germany).

Recommendations

38. At present, the calorimeter design requirements are not well motivated. The listed *requirements* with respect to position, time and energy resolution have to be related to the physics aim of improving and supporting the tracking information for electrons. Based on simulations one should determine which parameters would provide maximum sensitivity and what resolution values could be tolerated. The minimum requirements of acceptable energy, time, and position resolutions should be determined from simulations and clearly stated. Such information is essential for the selection of scintillator material and detector geometry, and is critical to the design concept of the readout, which should meet the required timing and energy resolution. The proposal should also quantify the overall efficiency/acceptance of the calorimeter. In general, the calorimeter parameters (e.g. crystal size, granularity etc.) have to be justified based on

specifications that are based on the simulations. Additional resources are needed in this area before calorimeter designs can be critically evaluated.

39. The calorimeter design would benefit from having background studies with full simulation of the detector. These full detector studies should determine the minimum design parameters needed for the calorimeter, which provides independent, but less precise, information than the tracker.

8.2 Cosmic Ray Veto

Findings

- The project presented a design for the cosmic ray muon veto based on the well-established technology of extruded plastic scintillator read out by WLS optical fibers and multi-anode PMTs. A SiPM-based readout is being pursued by the Lab and the project as an alternative technology. An additional gas-based readout system is also retained as a design alternative.
- Simulations of the electron backgrounds induced by cosmic rays are in a reasonable state and justify the specifications for veto counter's background rejection at the level of 0.01%. The simulations estimate the background level to be 0.025 ± 0.025 events out of a total background estimate of 0.17 ± 0.07 events over the nominal exposure.
- The reference design is based on three staggered layers of scintillator bars. Simulations show this design should meet rejection goals based on two-fold coincidence. The goal of the system is to represent less than a 1% impact on the detector both due to readout dead time and experimental lifetime due to detector service or local readout problems. The segmentation of the systems is driven by the scintillator extrusion technology.
- A prototype module developed for MECO has been used in both cosmic-ray and a test beam exposure to test both types of readout. Examples of early prototype extrusions were displayed. The final details of the optical design (e.g. number/size of fibers, mirrored readout and/or two-ended readout, and optical coupling of the fiber within the hole) will be specified based on the results of the described R&D plan.

Comments

- Additional background simulations are being processed and will be used to firm up the computed cosmic-ray induced backgrounds in the experiment. These results will be important for informing the technical design of the optical system and readout.
- The background from cosmic rays assuming, normal operation, is greater than 10% of the current background estimate (with 100% uncertainty). A local readout failure in the veto would either require downtime to maintenance or reduced the background rejection. The experiment should consider the relatively small incremental cost of adding an additional layer of scintillator as a way to ensure the veto system does not impact the operational live time of the experiment. An alternative method would be to use two-ended readout or splitting the readout across multiple readout front-ends.
- Be sure to fully exploit the design and operational experience gained by experiments that use this technology. Examples include MINERvA, CLAS pre-

shower calorimeter upgrade at JLAB, and the T2K-ND280 detector, which also use the alternative readout technology.

Recommendations

40. As full-statistics background simulations and light yield data become available both for cosmic ray backgrounds in the experiment and for backgrounds in the veto system (e.g. from neutrons), continue to revise the design in anticipation of the next design phase.

9.0 DAQ

Lead: Leon Mualem

Contributors: Eric James, Jonathan Lewis

Findings

- DAQ system is designed to use a custom Data Transfer Controller (DTC) to aggregate data from front-end Readout Controllers (ROCs)
- The readout of the front-end electronics is fully streaming, sending all zero suppressed data to the DTCs.
- DTCs combine data from a single time slice from multiple units and multiple detector components via an Event Builder Network and provide buffered events to the analysis software running on commodity computers
- Commodity computers process the event data and make trigger decisions to decide what data to pass on to be logged.
- DAQ/Trigger uses commodity hardware to maximize cost effectiveness where possible.
- The system plans on the capability of partitioning the DAQ system via an addressable timing/command link.
- The DAQ system has considered a multiple block architecture that provides a method of recovery if part of the system is unavailable.

Comments

- The fully streaming data acquisition system and block architecture are appropriate to meet the specifications and advantageous avenues of pursuit.
- Trigger software framework development is the responsibility of the project DAQ software effort, while the filter algorithms and their performance are the responsibility of collaboration physicists.
- DAQ expectation is for the trigger to reduce the data rate to under 1 Petabyte/year, but there is no requirement on trigger performance in the system requirements document
- DAQ system has not yet determined all the modes of data collection for the detector subsystems and calibration and diagnostic modes of operation.
- The interface with Slow Controls, accelerator and beamline monitoring are not defined

- The DAQ does not have requirements from offline analysis for any specific time ordering of data segments in files.
- The DAQ system should understand whether there are other experimental demands on rack space.

Recommendations

41. For CD-1, define reduction in trigger rate reduction required by offline data processing and storage limitations.
42. For CD-1, define potential trigger algorithms and estimate performance and computing requirements.
43. Define interface between slow control system and beam-line monitoring components
44. Review all data-taking modes (calibration, non-zero-suppressed, etc.) to confirm that the DAQ as planned can collect all data formats at the required rates.

10.0 Charge Questions

10.1. Is the design technically adequate? Is the design likely to meet the technical requirements? Are the physics requirements clearly stated and documented? Have these requirements been translated into technical performance requirements and specifications?

The overall design maturity for the Mu2e experiment is at the conceptual level and consistent with the detail necessary to support a DOE Critical Decision 1 (CD-1). The design is technically adequate for this stage of the design process. In some subsystems the design is equivalent to advanced conceptual design and in a few subsystems some additional design progress is necessary for DOE CD-1 requirements, e.g., sky shine shielding and the e-berm. A global evaluation of the entirety of the design across all subsystems provides confidence that the conceptual design is an adequate basis for moving to preliminary design and that the design will ultimately meet the Mu2e experiment requirements.

The physics requirements in most cases are well understood and drive the subsystem designs. The formal process of translating requirements into technical performance requirements and approved documentation is nearing convergence but needs to be accelerated and improved in preparation for the start of preliminary design and the upcoming CD-1 reviews.

A general concern of the committee is the status of simulations. While there is progress on simulations there is more work needed to justify design choices and to support the advertised performance of the experiment.

Recommendation

45. Complete the additional simulations studies that are necessary to confirm that the design is optimized to meet the physics requirements.

10.2. Can the design be constructed, inspected, tested, installed, operated and maintained in a satisfactory way?

While Mu2e is a very challenging experiment, it is anticipated that the design can be constructed, inspected, tested, operated and maintained in a satisfactory way. There are challenges with radiation safety and activation of components during operations that result in special design features and requirements for operations and material handling. The report includes specific comments and recommendations to be considered during the preliminary design, R&D, and prototyping phase.

10.3. Is there adequate supporting documentation to support the conceptual design and the transition to developing the preliminary design?

The draft Conceptual Design Report (CDR) and supporting documentation is generally adequate to support this technical review of the conceptual design. The presentations and discussions with the committee were extremely productive and helped to fill in gaps in the documentation. It will be important to continue to develop and approve additional supporting documentation for the reviews later this summer, e.g., R&D and testing plans

for Calorimeter and Tracker, interface control documents, and the additional requirements documents.

There were some inconsistencies in the presentation of information in the draft CDR that need to be resolved before the document is finalized.

Access to supporting documentation should be improved for future reviews either by providing access to the DocDB document database or by providing a website interface to the documents – preferred.

10.4. Are the risks (on technical, cost, and schedule basis) of the selected base design approach and alternatives understood and are appropriate steps being taken to manage and mitigate these risks? Have areas been identified where value engineering should be done? If value engineering has been performed is it documented?

A formal process of risk identification, assessment, and mitigation is in place. The design incorporates mitigation strategies and alternative design options continue to be considered as part of the design process. This risk management process is a good approach but the results of the process should be strengthened as the project moves to the next design phase. Necessary improvements include developing additional mitigation strategies, clarifying the status of items, and including the decision schedule for choices between options.

Additional work preparing simulations and detailing R&D and prototyping plans is necessary to transition to preliminary design and to reduce the overall risk.

Recommendation

46. Prepare a Mu2e R&D and prototyping plan prior to CD-1.

A key risk referred to in the risk register is the issue of sky shine from stray neutrons. This is a potential “show-stopper” for this experiment. The mitigation strategy to reduce this radiation hazard relies on the concept of an “e-berm,” or electronic monitoring of beam intensity versus position to identify excessive beam loss. The e-berm would immediately stop further beams until the source of the loss is determined and rectified. Such a system has not been vetted for safe operation.

A formal value engineering program or systematic method for improving value is not in place but the products of a such a program are evident in the evaluation of the requirements that drive cost and schedule, alternative and option analysis, and assessments of experiment performance based on design options. Value engineering should continue into the advanced conceptual and preliminary design phase and the committee identified some additional options to consider that are documented in this report. A program to ensure that detector specifications can be strictly traced back to physics requirements can help identify areas for future cost reduction.

It is likely that the results of the costing exercise currently underway will result in the need to identify cost reduction opportunities and to complete additional value engineering.

A lack of resources is constraining current progress and the adverse consequences to schedules will grow given competing demands from other experiments and programs. The potential addition of the g-2 experiment will further complicate this issue.

Recommendation

47. FNAL management should undertake a global assessment of the resources required for the upcoming suite of experiments (and the resources available), establish priorities, and identify scope that can be outsourced.

10.5. Are the project organization and lines of responsibility clearly defined and sufficient to ensure the successful engineering and design of the project? Are the design interfaces between the Accelerator Systems, Experimental Facilities, and Conventional Facilities groups understood and well enough defined to ensure a coordinated effort and an integrated design? Is there a reasonable plan in place for implementing configuration management to ensure changes to the technical requirements/specifications are controlled and communicated to all affected groups?

The overall project organization and responsibilities are sufficiently well enough defined to support successful engineering and design. The organization includes a Technical Board responsible for coordination among the Level 1, 2, and often Level 3 managers and a Risk Management Board. The central project organization includes two project engineers (mechanical and electrical) that are responsible for managing project interfaces and ensuring that there are appropriate requirements and interface documentation. There is a need to identify additional resources and clarify responsibilities at the subsystem level, e.g., radiation protection responsibilities within the accelerator system. The additional resources and clarified roles are necessary to ensure proper integration and coordination.

There seems to be a reasonable general understanding of interfaces between the design groups. There will need to be additional progress on requirements and interface documentation and approval in concert with finalizing the Mu2e Conceptual Design Report (CDR). These documents are complimentary to the designs described in the CDR and will serve as the primary basis for technical configuration control and the communication of changes to project participants. A number of critical requirements documents are in place but a major effort to improve the maturity of the requirements and interface definition should be completed in preparation for the DOE CD-1 review. An evaluation of the real importance or necessity of requirements will be an important element of future value engineering and cost containment efforts.

Recommendation

48. Intensify efforts to complete and approve additional requirements and interface control documents prior to the DOE CD-1/Conceptual Design Review.

The project is resource constrained and the result is a highly factorized effort with subsystem teams having limited resources and time available for integration efforts beyond their subsystems, e.g., cabling. The project engineers are an essential to the integration and interface definition efforts but not sufficient for the next phase of the project. Additional resources are needed to prepare for successful CD-1 reviews and transition to the preliminary design phase of the project.

Recommendation

49. Develop a plan for adding resources to the Mu2e subsystems and improving the overall integration effort.