2022 pre-CD-3A Director's Review of MOLLER

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Executive Summary

The Measurement of Lepton-Lepton Electroweak Reactions (MOLLER) experiment at Thomas Jefferson National Accelerator Facility (JLab) proposes to measure the weak mixing angle, $\sin^2\Theta_W$, to unprecedented precision of 0.1% at low energy, thus improving our understanding of the running of this fundamental constant and providing a sensitive probe of new physics. The purely leptonic scattering channel is complementary to current efforts and future proposals to measure A_{PV} from e-p scattering, and is particularly relevant in an era where a number of other anomalies have emerged in the lepton sector. The theoretical uncertainty on Q^e_W is currently <0.5% due to recent progress on the full 2-loop calculation, which compares favorably to the expected experimental uncertainty of 2.4%. The MOLLER experiment represents a unique opportunity for JLab that leverages the large investment made in the 12 GeV upgrade. The experiment is a compelling opportunity for the US Department of Energy Nuclear Physics (DOE-NP) program and represents a 5-fold improvement over the last measurement made in the E158 experiment at SLAC. Mission need was recognized in 2016 and the science motivation for MOLLER remains strong.

The MOLLER Project received CD-1 approval in January 2021 and completed a Status review in November 2021 where the Project was determined to be on track. Due to some relatively minor delays in the design work throughout the COVID pandemic and some recent turnover in the management office, the Project has decided to push a CD-2/3 review back to summer of 2023, 8 months later than originally planned. Overall, this committee found the design work is approaching the 90% level and the Project will be ready for an internal Final Design Review (FDR) in December 2022 and an independent FDR in January 2023.

In order to efficiently advance the schedule, the MOLLER Project is requesting a CD-3a approval in advance of their CD-2/3 review. The CD-3a will enable long lead-time and other essential procurements that will allow the experiment to stay on track to produce a physics result on a timescale competitive with the new precision electroweak physics results that will be emerging from LHC Run 3 and the e-p scattering experiment at Mainz. Furthermore, these advance procurements will greatly reduce the heightened risk of supply chain issues that have emerged as a result of the COVID pandemic. The committee finds the justification sound and believes these advance procurements will benefit the Project, the laboratory, and the agency. The MOLLER Project is in a relatively unique position of having received their full funding through the Inflation Reduction Act, so meeting the obligation profile is not a concern. Entering into a subset of procurements early in 2023 will help reduce the peak in the load on laboratory procurement staff needed to exercise the bulk of the MOLLER procurements in FY24. Finally, the Project estimates a 4-month reduction in the schedule to completion which represents a $500k savings in Level of Effort project management in the long run.

The committee finds that the MOLLER Project team and scientific collaboration have made impressive progress since their CD-1 approval. Designs have stabilized for all the critical components and are approaching the 90% maturity level appropriate for a FDR.

All of the project tools needed for CD-2/3 approval are in place and earned value is already being used to actively manage and track progress. The documentation needed for CD-2/3 approval exists in high level drafts that will be easy to be finalized on the anticipated timescale for the review. A common thread emerged that several groups are feeling the strain of meeting the workload required by MOLLER and other responsibilities at the laboratory. This has been exacerbated by a natural attrition of staff that occurred during COVID. The laboratory is actively recruiting to augment the technical workforce at the laboratory, especially the Hall A/C scientific and engineering staff. Overall, the Project, laboratory, and the scientific collaboration are working harmoniously to make MOLLER a success. We recommend that the project proceed with the independent FDR scheduled in January, pursue a CD-3a for advance procurements, and schedule the CD-2/3 review later in FY23.

Answers to Charge Questions

1. Is the project team effectively executing the work? Yes Are technical issues appropriately and proactively being addressed? Yes Are the proposed CD-3A long-lead procurements appropriate? Yes, but the Project should consider consulting with the agency about adding the magnet power supplies to the request.

2. Are the cost and schedule estimates credible? Yes Do they include adequate scope, cost, and schedule contingency? Yes Is the estimate for the proposed CD-3A long-lead procurements appropriate? Yes

3. Are environment, safety, and health(ES&H) and quality being properly addressed given the project's current stage of development? Yes

4. Is the project being properly managed? Yes Are risks being effectively managed? Yes Is the management team in place to successfully execute the CD-3A scope? Yes

5. Is the project appropriately addressing recommendations from prior DOE SC reviews? Yes

6. Is the project ready for CD-3A approval? Yes

SC-1 Management, Cost & Schedule, ESH&Q

Committee Members: Glenn Young

Findings

- The MOLLER Project has produced the basic set of documents required to move forward from CD-1 to CD-3a and further CDs. These include documents for system requirements, interface control, project management and management team, risk registry, procurement plan and acquisition strategy, a hazard-analysis report (recently upgraded from preliminary), a quality assurance plan, the WBS dictionary and associated resource loaded schedule using the DOE approved Primavera P6 framework, and a TDR (in draft form).
- Familiar project management tools employed in earlier JLab projects such as the 12-GeV Upgrade are in evidence and obvious use. Responsibility matrices exist, budgets have been defined, an account structure is in place and in use, EVMS reporting has been practiced for several months and variance reports are submitted. Monthly PARs reporting has started. The IPT has begun regular monthly meetings. Project management reports on project status at the annual MOLLER Collaboration meetings. CAMs have had their EVMS training.
- A QA report has been run on the P6 implementation of the MOLLER resource loaded schedule with good results.
- NSF scope is in P6 (but not COBRA). Starting in October the project can generate NSF schedule metrics, which aids in tracking that scope. A similar approach can be used for non-US-funded scope.
- Eighteen formal baseline changes have been made, including alignment with the overall Hall A schedule and procurement of prototypes for the magnet power supply and the exit window, both key items.
- Tracking of labor requirements and usage is underway.
- Over one hundred procurements are identified, with acquisitions plans in place for those exceeding $1M in cost, an acquisition review board in place for these, and a designated procurement group formed and operating in concert with project management.
- An ES&H plan is in place, with requirements flowed down from the overall ISM plan at JLab. These requirements can be flowed down to subcontractors on the MOLLER project using regular subcontracting procedures.
- MOUs and CRADAs are in place or under development with key collaborating institutions who are taking on construction activities in support of MOLLER.
- KPP are defined, both Threshold and Objective.
- A running plan that will allow achieving the proposed UPPs has been put forward to Lab management and the agencies.
- A point estimate cost of $48.2M has been developed, including a contingency of $10.8M. The current cost range is $45.M - $55.4M, or -5% to +15%, which is

expected based on the maturity of the various estimates (Class 2 and/or 3 at present.)

- Three different CAD systems are licensed and in use, Inventor for WBS 1.02, NXCAD for WBS 1.03 and 1.06, and Solidworks+Inventor for WBS 1.04 and 1.05. Regular checking and control of the overall 3D model is held by one member of JLab engineering, with a monthly publication of the JT file, and with files held in the JLab document repository. Final drawings and specifications are filed in the JLab document repository with their original numbering.
- An interface matrix is defined and in use, and interface control documents created for all identified active areas in this matrix. Regular discussions are held and conflicts are identified and resolved.
- A review sequence including CDR, FDR, Hall A integration review and finally an experimental readiness review is defined and in initial stages of use.
- A QA plan is set forth and QC responsibility assigned to L2 managers.
- The relevant chapter of the JLab electrical safety manual has been updated to deal with the issue of custom-fabricated electronics components that have not been reviewed by a Nationally Recognized Testing Laboratory. This is needed in addressing the use and deployment of the several custom electronics components which will be fabricated for MOLLER.
- Regular safety walkthroughs are conducted.
- An approved vendor list for pressure vessels and other welded structures is in use.
- A standard training 'stack' that must be completed before access to Hall A or issuance of a radiation badge is granted is defined, communicated to the Collaboration, and in use.
- A risk analysis has been performed starting from the P6 resource loaded schedule. Estimate uncertainties are defined according to a graded scale for all P6 activities. A separate scale was used for labor and material activities. In parallel discrete risks have been analyzed and are assigned to specific activities using a user defined field in P6. The parts of the project funded from other sources than the DOE are included in this for schedule risk
- The risk from transit - whether to build and assemble remotely and then ship, or bring components to JLab for assembly, has been considered.
- The risk from having sole-source for GEM foils, namely CERN, is included. Earlier major risks, in particular for coil potting resin radiation tolerance and radiation damage to the quartz detectors, have been removed via a targeted program of prototyping. The new risk due to recent large inflation has been included and modeled. The schedule risk arising from limited commercial shop availability for performing large aluminum weldments is included.
- Current values for Estimate Uncertainty is $5.6M (16%), discrete risks is $2.4M (7%) and full analysis is $7.5M (22%)
- Labor rates are currently escalated from FY2018-2019

Comments

- The MOLLER Project needs to arrange a review of the TDR.

- Regular formal review and updating if needed of the ICDs by the management team, L2s and all lead subsystem engineers is a good practice.
- A calendar of upcoming CDRs and FDRs plus the expected date for the Hall A ERR would be useful. This could be tied to specific events in P6 and updated for future reviews to demonstrate progress.
- QC flowdown via subcontracts is planned, but items funded by NSF and non-US sources require some other mechanism to assure quality. MOUs and CRADAs are tools for this. Site visits by management to review plans and mutual understanding of what is being built, and to hold CDRs, FDRs and first-article inspections, are also useful in this circumstance. Clear expectations for initial documentation before starting production and then for final documentation for the permanent records at JLab should be established early with all collaborating groups that are producing equipment for MOLLER.
- The open position for a QA professional does need to be filled soon.
- A formal means of communicating observations and resulting suggestions or action items from safety walkthroughs, both at JLab and at other institutions performing work for MOLLER, would be helpful to ensure a uniform high standard.
- The project acknowledges the risk due to labor rate increases and plans a re-estimate upgrading to FY2023 labor rates using most recent guidance from DOE.
- There is an ongoing risk due to inflation for materials costs in particular. A program to track key materials, such as shielding concrete, steel and aluminum would help track and quantify those risks going forward, providing guidance to allocation of contingency and timing of large procurements.
- An in-depth discussion with Lab management and agency personnel about expected labor rates, and a what-if analysis of increases to the project timeline and EAC, would help manage this risk, which has grown in significance the past two years. The large BA available may help mitigate risk going forward.
- Determination of which engineering and design efforts that can be completed soon would help manage labor-cost risk going forward.
- Examination now of other projects' experience with defining and then performing engineering and design for tooling and fixturing that will be needed for installation would help in planning the later stages of the project and ensuring adequate cost reserve and schedule contingency exist at that time. The recent installation of the SBS in Hall A could provide a recent cost-basis and labor-basis reference.
- There is a significant ramp up in spending from $5M in FY23 to $18M in FY24, the Project should continue to proactively work with laboratory procurement specialists on timely placing the ~115 procurements prioritized according to float.

Recommendations

- Proceed with the independent FDR scheduled for January 2023.
- Work with the agency and the laboratory to obtain the authorization for the CD-3a early procurements as outlined in this review.

SC-2 Target, Infrastructure, and Installation

Committee Members: Chris Polly

Findings

- The target design has stabilized on Model 21 as of January 2022 and significant progress on CFD simulations have been completed.
- The CFD for the reduction in density of the LH2 target was verified against known data from Qweak and predicts the Moller target will meet the specification of <1% density reduction.
- At 30 ppm, target density fluctuations are projected to be the largest additional contribution to the broadening of the pair width when extracting Apv. This should be compared to the 82 ppm statistical width where it adds in quadrature.
- The time-dependent CFD has been run for a duration of 10 seconds and predicts a 16 ppm contribution to the noise term in extracting Apv, which is better than the 30 ppm currently budgeted.
- The planned prototyping of the pump mechanism has been foregone in favor of a full vibrational analysis.
- Installation of the new beamline has not yet been possible due scheduling conflicts with operating experiments.
- Significant value engineering has been performed since the last review to optimize shielding materials (Pb, tungsten, concrete, and barite concrete) for cost, performance, and waste reduction.
- Dependencies on off-project laboratory infrastructure deliverables have mostly been met with the exception of still needing the ESR2 refrigerator upgrade to achieve the full beam power needed to satisfy the Objective KPP.

Comments

- The time-dependent CFD has made good progress and the results look very promising for meeting the key systematic requirements. The team should continue as planned to pursue modeling for longer timescales, so 30 second results can be compared to the current 10 seconds of modeling.
- The CFD model for density reduction was validated against the measured density reduction in Qweak. It would be good to also benchmark the density fluctuations to build confidence in the model.
- The current design spec is to run the target at 20K. Past experience has shown that even a 1K further reduction in temperature can still substantially reduce density fluctuations in the LH2 target. The target engineering team should aim for

keeping this option available to provide an additional handle should the density fluctuations be larger than anticipated.
- Safety for the LH2 target is being thoroughly addressed and benefits greatly from the past experience at JLab.
- The Project should continue to pursue options for an improved BCM readout scheme that would bring an individual monitor's performance closer to the 10 ppm budget and reduce the need to average multiple monitors.
- The Alignment Task Force should finalize the list of tolerance requirements based on what is reasonably achievable while ensuring those tolerances will also meet the requirements from the physics program. This should be completed by the Independent FDR and will address the outstanding recommendation from the Sep 2021 Director's Review.
- The Project should work with the lab to get the new beamline installed and gain operational experience prior to the start of MOLLER.

Recommendations

- None

SC-3 Spectrometer and Beam Pipes

Committee Members: Ruben Fair, Dave Harding, Soren Prestemon

Findings

- The MOLLER Project has been designing the spectrometer based on extensive simulations of the physics, especially the anticipated backgrounds. The recognition that even minute amounts of ferromagnetic material in the spectrometer would introduce backgrounds through asymmetrical scattering has guided a campaign to rigorously purge all such contaminants..
- Detailed design work on the upstream toroid is in progress with extensive calculations.
- Some prototype coils for the downstream toroid have been received and the others are due shortly. Measurements and tests of the coils match well with the extensive calculations. The contract for prototype fabrication includes fixed-price options for either seven or eight production units (depending on whether the project chooses to use the prototype coils as spares) with the exercise date coming in spring 2023.
- All the conductor for the downstream coils is in hand, mitigating the cost and schedule risks of that procurement.
- The power and water manifolding for the downstream coils, including the vacuum penetrations, has been designed, as have the support structures with suitable adjustment capability for alignment.
- Prototype power supplies are on order and testing is expected in March 2023.

- The most challenging aspects of the beam tube and vacuum windows have been addressed with prototypes.
- The DS toroid team has prepared a comprehensive list of all the required CD-3a procurements.

Comments

- The spectrometer team appears to have a good understanding of the tolerances required for magnet fabrication, assembly, and installation alignment. Mechanical tolerances achievable with ordinary care meet the physics requirements, in many cases with a significant margin. While much work on the tolerances has been captured in MOLLER-INSTALLATION-SRD-001, a few numbers still need to be entered. It seems reasonable to wait until after the internal FDR to provide the summary Table 8, with looser but acceptable tolerances, to serve as a KPP.
- Failure to exercise the downstream toroid coil option before it expires would (re)introduce serious cost and schedule risk. Including that procurement in CD-3a is appropriate.
- The upstream toroid design continues to lag other design efforts, apparently due to earlier staffing shortages. Continued attention will be necessary, including expeditious reviews.
- The US toroid team should review the list of procurements and determine if there are any other long lead items beyond the conductor that should be requested in the CD-3a.
- The magnet power supply design is not yet validated with tests of the prototype due to supply chain issues faced by the vendor. These delays suggest that it would be prudent to exercise the option for the production supplies as early as possible after the design is confirmed. This would require inclusion in the planned CD-3a.
- The reported uncertainties in the bellows fabrication price, schedule, and quality fully justify inclusion in CD-3a.
- With a long fabrication time and few potential vendors for the downstream magnet enclosure, getting an early commitment through CD-3a is well-advised.
- The Spectrometer L2 Technical Lead seems a bit overcommitted at the moment with the flood of drawings from multiple engineers, designers, and drafters requiring his review and approval before they can be released. Detailed review by an experienced engineer is essential; identifying an alternative reviewer might be useful for the short term.
- The Project should continue working with the laboratory to identify a suitable space where coil assembly and testing can be performed on the timescale needed by the Project.

Recommendations

- The Project should consult with DOE on exercising the power supply option in the CD-3a request, with the stipulation that the prototype pass the specified acceptance tests before the option is exercised.

SC-4 Detectors, Trigger, and DAQ

Committee Members: Haiyan Gao, Tanja Horn

Findings

- The MOLLER Project has been identifying design parameters and working towards final design drawings. SRD and PDRs have been completed and a draft Technical Design Report has been produced.
- The project detectors and DAQ and Trigger are supported by the combination of DOE MOLLER MIE, the NSF Midscale Project and the Canadian Foundation for Innovations (CFI) Project.
- Detectors
    - Pre-production prototyping and beam tests of all five detector types are ongoing. Two of the five types were found to meet specifications. Most beam tests should be completed by the end of 2022 and this should be sufficient for the design. Additional testing is planned for May 2023.
    - 5 different quartz types have been evaluated for their transmission loss with respect to irradiation. A preferred choice has been identified
    - The detector design geometry is being implemented into the Geant4 simulation. Validation is planned for January/February 2023 followed by full simulations
    - There is one open recommendation tracker item (identifier: 2021_11_IPR) related to the barrel segment patch panel
    - The foils for the GEM detector prototype are in-hand. The full detector will need 28 GEM foils.
    - The design of the GEM rotator with (linear) radial and rotational motions has been completed and FEA studies for displacements and stresses have been conducted. Vibrational modal analysis is underway.
    - The pion detector parts are not yet fully specified but the rough specifications are known, e.g., the characteristics of the PMTs (gain, anode current, window material). The cabling setup has been maturing. There are not yet engineering drawings for the cable layout.
    - The design of the support structures for the main detector and Shower-Max appears quite mature and FEA studies have been performed.
    -
- DAQ/Trigger
    - Mature design documents as well as parts lists are available

- The full “PMT + pre-AMP + ADC” signal chain was tested at a beam test in Germany in Oct. 2021. The results are encouraging. Additional tests will be done in November/December 2022
- Supply chain issues are a problem for the procurement of DAQ/trigger components, e.g., lead times can be 40 weeks.
- Resources for the development of firmware and system integration are limited
- There is close collaboration between JLab and universities
- The team follows the experience and results from the SBS experiment. The same VTP design for the GEM modules with APV chips connected to MPD is used. To date no failures due to radiation have been reported.
- The MOLLER team has more than 200 APV-25 chips in hand, and the remaining chips can be easily met by what SBS has.

Comments

- The MOLLER Project has been making excellent progress in the areas of detectors and DAQ. The team is on track to complete 90% of the design prior to DOE OPA CD2/3 review in the summer of 2023.
- There appears to be a coherent plan for integration of detectors and DAQ and triggers supported by the DOE MOLLER MIE, the NSF Midscale Project and the Canadian Foundation for Innovations (CFI) Project.
- Detector:
  - The team may consider expedient completion of prototype beam tests, validation of the detector geometry and full Geant simulations. In the beam tests, the team may consider testing multiple detector components together, e.g., main detector rings.
  - The team may consider specifying any remaining detector parts, e.g., pion detector as soon as possible.
  - The team may consider keeping close track of the production schedule at CERN for the GEM foils for the full detector.
  - The team may consider expedient completion of the final design drawings
  - The team should consider closing the open recommendation tracker. (2021_11_IPR) item as soon as possible. The item is presently open as connectors are still being selected. However, this is not a major issue as workable (multi-pin) and fall-back (BNC) solutions have been identified
- DAQ/Trigger
  - While there are no major technical issues with the DAQ, a significant amount of work is required, especially in the area of firmware. Additional workforce will be beneficial so that the DAQ can be ready early for test stands and software development.
  - The team should consider starting procurement of DAQ/trigger hardware components after completion of the final design review

- The team may consider keeping close track of the development of firmware and system integration, and in particular if responsibilities are divided over several institutions.

Recommendations

- None

MOLLER Director's Review Committee

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