2021 MOLLER Status Update
Director's Review

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Table of Contents

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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 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 at 1.4% with an expected reduction to <0.5% after the full 2-loop treatment is complete, 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 E158. Mission need was recognized in 2016 and the science motivation for MOLLER remains strong.

The MOLLER experiment was approved by the JLab PAC in 2009. There was a successful Science Review convened by DOE-NP in 2014. A Director's Review was held in 2016 to assess the conceptual design and provide advice on pre-project planning and development. MOLLER received DOE Critical Decision-0 (CD-0) "Approve Mission Need" in December 2016, which was followed by a pause due to lack of funding. In anticipation of a project restart, a Director's Review was held in both 2019 and early 2020 to assess the progress of MOLLER towards CD-1. In August of 2020 JLab Management convened a Director's Review and charged the review committee with evaluating the preparedness of the MOLLER Project team for an upcoming CD-1 review. A successful CD-1 Independent Project review was held in October 2020, with CD-1 approval granted in December 2020. The current 2021 Director's review was conducted to determine if the experiment is on track for a CD-2/3 combined review in the fall of 2022. Another Director's review is anticipated prior to the DOE CD-2/3 review.

The committee found that the MOLLER Project Team continues to make impressive progress since the last Director's review in August 2020. The Project completed the conceptual design and passed the CD-1 review with a few recommendations that they are addressing appropriately. The work to complete preliminary (60%) and final (90%) designs will be the primary focus over the coming year. The Project has already completed a number of these reviews and has plans established to complete the remaining technical reviews over the coming year. Their procurement strategy appears sound at this stage with the Project taking steps to establish contracts for prototypes with options to execute for the construction of the critical path spectrometer magnets. Conductor has already been

purchased. The Project has recognized the impact COVID-19 has had on supply chains and is taking steps to mitigate schedule risk. A major development has been securing funds from both the NSF and CFI for the construction of detector and electronic components.

The Project Team has done an outstanding job of rolling out an EVMS system well ahead of the projected CD-2/3 schedule. An activity-level RLS has been established with change control implemented immediately after the CD-1 approval. The Project has a solid plan to also track the progress of external contributions from the NSF and CFI funding sources fully integrated into their P6 schedule and milestones. The documentation required for the CD-2/3 approval exist in advanced draft forms and the Project should have no issues with producing the final versions on the timescale of the CD-2/3 approval scheduled for fall of 2022.

The Moller Project should continue to complete the design work over the coming year and is on track for obtaining CD-2/3 approval towards the end of 2022.

Answers to Charge Questions

1. Progress: Is the MOLLER team effectively executing the work? Yes Is the design progressing satisfactorily and are technical issues appropriately and proactively being addressed? Yes Is the project making satisfactory progress since CD-1 and on track for CD-2/3? Yes

The design is progressing satisfactorily with all systems on track for 90% design. Some systems have already passed the 60% design review and a large number of design reviews are scheduled for 2021/22. Technical issues raised have been systematically addressed. Simulations have informed shielding requirements and interferences identified at CD-1 have been addressed. Detector design is moving from concept to prototyping and testing. The Project is on track for a CD-2/3 review in Q1 of FY23.

2. Cost and Schedule: Are the cost and schedule estimates credible? Yes Do they include adequate scope, cost, and schedule contingency that are based on a project-wide risk analysis? Yes

The cost and schedule estimates are credible with an appropriate level of contingency for this stage of the design. In addition to estimate uncertainties based on the estimate type, the Project has a thorough risk registry identifying discrete risks.

3. Partnerships: Is the proposed distribution of scope between the partners adequately defined? Yes Does the project have an appropriate framework to plan for the utilization of contributions from DOE and non-DOE partners? Yes

The non-DOE partners in MOLLER are the NSF and CFI. NSF and CFI each support different aspects of detector construction. These contributions each have their own Level 1 structure in the WBS as shown by Jim Fast in his Project Overview. Details of the separate contributions were explained by Mark Pitt in his introduction to the detectors. The lack of contingency on the NSF contributions to the detectors is a concern since the only recourse would be a reduction in scope.

4. Environment, Safety, and Health (ES&H): Is ES&H being properly addressed given the project's current stage of development? Yes, although the ES&H presented at this review was very brief. A more thorough discussion should be included at the next Director's review.

5. Management: Is the project being properly managed at this stage? Yes Has the management team made adequate progress on the prerequisite requirements for CD-2/3approval and is there a sound plan for their completion? Yes Will the project be ready for the pre-CD-2/3 review in Fall of 2022? Yes

The Project team has made impressive progress that includes fully deploying an Earned Value Management System that began immediately after their CD-1 approval. Changes are already being tracked and EVMS reports are being produced. The main work over the

next year appears to be the 60% and 90% design reviews, for which the project has a robust plan.

6. Reviews: Is MOLLER appropriately addressing the recommendations from prior DOE SC reviews? Yes

There are a few cases of lingering recommendations where it is unclear how to formally close out vague or open-ended recommendations. We encourage the team to be more proactive in closing out recommendations (with documentation) that have been met adequately for the upcoming CD-2/3 review. For example, this committee would consider that recommendations to pursue two-loop calculations are not in scope for the MIE project, and comprehensive simulations of the combined detector/hall are already in hand.

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

Committee Members: Heather Crawford, Chris Polly

Findings

- The MOLLER Project Team has remained constant since CD-1, with the exception of one new admin, and a change in the leadership in WBS 1.03.
- The NSF and CFI proposals for portions of the MOLLER experiment scope were successfully funded. These are integrated into the overall schedule as projects 2.0 and 3.0 for NSF and CFI respectively.
- The installation of MOLLER has been separated into WBS 1.08; James Fast is the acting L2 manager for this WBS.
- The KPPs remain unchanged from CD-1, except for a relaxation of the threshold KPP related to the spectrometer magnetic field strength stability to < 500ppm (from < 100ppm previously).
- Project dependencies are understood. All are on-track, though the ESR-2 effort is delayed. This delay does not yet impact the MOLLER schedule.
- The JLab PSSO is in the process of hiring a QA professional.
- The project has been exercising EVM and change control since approximately January 2021.
- An interface matrix has been developed and ICDs are all in at least a draft form.
- The project is carrying 66 open discrete risks, including 5 HIGH risks.
- Quantitative risk analysis (Monte Carlo) is now being performed in Safran.
- The PHAR has been updated to include COVID-19.
- The NSF and CFI scope are being integrated into P6; this will be completed by the end of the calendar year.
- CD-2/3 early finish has slid by 2 months relative to CD-1 date; CD-4 EF has slid by 4 months
- The project critical path runs through CD-2/3 and equipment readiness. This previously ran through the completion of SBS operations.

Comments

- The overall status of the MOLLER project is excellent. The management and technical teams have made impressive progress since the last review and should be commended on their work to date.

- The state of the Project Management documentation (PPEP, AS, RMP etc.) are very mature. These documents will easily be ready for CD-2/3 next year and are in fact largely at the necessary stage already.
- The MOLLER Project team is clearly aware of and monitoring the status of the delayed End-Station Refrigerator 2 (ESR-2) project. The project should continue to closely follow progress on this front and be prepared to raise flags should the ESR-2 approach the critical path for MOLLER.
- The COVID-19 risk as included in the risk register and carried by the project is due for review. In addition to reviewing the risk of direct impact of delay due to COVID-induced workplace restrictions, the project team should consider the addition of discrete risks associated with likely supply chain impacts.
- The rolling out of the ePAS system at JLab for work planning and control is likely to create work with respect to additional documentation for the project team. The impacts of this change for the project should be considered as a discrete risk for the project.
- Restrictions associated with assigning contingency on the NSF portion of the MOLLER experiment caused concern within the committee that the detector systems which are NSF scope could be at risk. We would suggest that the project team re-evaluate the risk assessment and potential impact on the scope for the detector area considering this constraint.
- The laboratory approach to bring on a QA expert in the Project Services and Support Office (PSSO) to work with MOLLER (and other JLab projects) is a very appropriate way to address the prior review recommendation for a QA expert on the project.

- The MOLLER project team has made substantial updates to their resource-loaded schedule effectively addressing the recommendations from previous reviews. The maturity of the schedule is ready for a CD-2/3 review. The costs are fully captured, though there remains work to update/accurately capture the NSF and CFI costs.
- The project should explicitly indicate milestones that arise from external dependencies in their milestone definitions.
- The approach to incorporate the NSF and CFI parts of the MOLLER experiment into the P6 framework was very well thought through. The fact that the project can status and report with and without the partner contributions is key and will serve them well going forward.
- There remain a few areas in the resource-loaded schedule where resource leveling is required, which the project has recognized. In particular, the installation resources need to be re-evaluated and leveled, a final step which will allow the project to close out the recommendation from the prior review related to generating a detailed and integrated schedule for installation.
- Currently the project does not include un-costed labor in their P6 schedule – this is reasonable for most areas of the project, especially as the bulk of the scope involving un-costed personnel from university groups has moved to the NSF/CFI parts of the experiment. That said, for the installation phase (WBS 1.08), we

suggest the project team explicitly include un-costed effort. This will be useful in not only gaining an overall picture of the total effort in this critical phase, but can provide guiding input to university grant renewals in the intervening period.

- While an ES&H talk was included, this talk alone did not fully serve the intended purpose of conveying the importance of safety in the workplace culture for JLab and the MOLLER project. In addition to strengthening this presentation (see appendix), the project should consider highlighting the importance of the safety culture in other presentations.
- It is understood that Jefferson Lab is undergoing a significant change to the work documentation and activity approval process. The new WCD application will include training and identifying electrical workers to perform specific tasks. The full implementation date for the new application was not mentioned. Presumably this application will be ratified well before installation of MOLLER equipment is started.

Recommendations

- In advance of the pre-CD2/3 review, the project should re-evaluate the risk registry, specifically with respect to COVID-19 direct and in-direct (supply chain) impacts.
- In advance of the pre-CD2/3 review, the project should ensure that spikes in the resources required in the schedule have been leveled such that the project can succinctly describe where the required personnel will be coming from.
- Present a more thorough ES&H discussion at future reviews.

SC-2 Target and Infrastructure (Detector Integration & Shielding)

Committee Members: Tanja Horn, Chris Polly

Findings

- Following CD-1, installation and alignment of the target and experiment elements to the nominal beamline have been moved to a new WBS 1.08 (Installation).

- The target susbsystem (WBS 1.02) includes vacuum system, hydrogen and helium gas service, target loop, target motion and target controls. The target window scope was moved into 1.02 after CD-1.
- The target cell design is required for the target loop and target motion design. CFD simulations are used to inform the target cell design. The required performance parameters have been established for steady-state simulations. Time-dependent simulations are ongoing
- Infrastructure and Integration (WBS 1.06) includes incoming beamline modifications, hall modifications, particle shielding and electronics hut, cables and low-voltage/high-voltage power supplies and detector frames and supports. The deliverables are: shielding enclosure for the magnet power supplies, electrical power to the magnet supplies, and LCW to magnets and magnet power supplies
- A combination of G4 and FLUKA simulation is used to determine the projected radiation doses relevant for the site boundary and inside the experimental hall. The G4 model has been shown by the Jefferson Lab RadCon group to be a reliable indicator of the site boundary dose
- Shielding calculations are available to demonstrate radiation doses and impact on specific detector components. Additional details have been added since CD-1 and impact studies are ongoing.
- Shielding requirements have been defined and interferences defined. Since CD-1 infrastructure solutions resolving the interferences have been found.

Comments

- The design of target loop and motion depends on the design of the target cell. The committee suggests to complete the target cell design expediently as the design progress of other components depend on it and engineering is required before CD2/3 to complete these designs
- The committee suggests to closely monitor the commissioning and performance of the beamline and to gain operational experience early as relevant for the experiment
- The radiation simulation and shielding studies are very mature and the communication between the simulation and E&D teams is well established. The committee suggests to finalize the shielding design expediently as detector integration and their infrastructure depend on it.

Recommendations

- None

SC-3 Spectrometer, Collimators and Beam Pipes

Committee Members: Soren Prestemon

Findings

- Alignment tolerances have been studied and documented both for magnets and collimators.
- The upstream torus (US) system design has been contracted to MIT to generate 60% and 90% designs.
- The project has chosen a segmented design for the downstream toroid (DS) system.
- The torus design utilizes the radiation-tolerant CTD403 for the impregnation of the coils.
- The project noted that the 1.03 WBS element is significantly understaffed compared to the project forecast.
- Conductor for the DS coils has been procured and received.
- A vendor contract is in place for a prototype DS coil, with options for production coil fabrication.

Comments

- We commend the project for downselecting to the segmented coil design for the Toroidal magnet, enabling the team to focus on developing the final design and fabrication plan.
- The recently approved vendor contract for the toroid magnet positions the team to systematically advance the spectrometer and to proceed with a coil prototype fabrication, and the contract approach with options should allow for timely transitioning to production once the prototype is vetted.
- The use of CTD403 cyanate-ester resin is well-motivated by the radiation load anticipate on the magnet system, as they are arguably the most radiation-resistant impregnation materials available. Cyanate esters have the potential to exotherm and it is strongly advised to fully vet the impregnation process tools in advance of their use on coils.
- The team should further clarify the role of the coil prototype and how its fabrication and testing will impact the magnet production.
- The project should specify and document the metrology approach for all elements of SC-3 scope.
- The project is encouraged to prepare a staffing plan for the spectrometer scope to enable SC-3 to achieve progress needed for CD-2/3, and present the plan at the IPR.

Recommendations

- If the apparent supply chain issues arising from COVID-19 for the power supplies persist, the Project should explore options for advanced procurement potentially including a CD-3a approval.

SC-4 Detectors

Committee Members: Tanja Horn, Brent Vandevender

Findings

- Details of the integrating and tracking detector systems (WBS 1.04 and 1.05) overall scope, budgets, schedule, risks and interfaces were presented by the Level 2 manager. Presentations for the integrating and tracking detector systems were also included though the scope was limited and no technical details were presented
- Since CD-1 an NSF Physics Division Midscale grant and a Canada Foundation for Innovation/Research Manitoba grant were awarded.
- The distribution of scope between the partners is adequately defined. The two grants cover the Integrating and Tracking detectors. The Project scope covers additional detector modules as radiation damage replacements.
- The roles of the DOE and non-DOE partners and their communication and integration are well established.
- Much technical progress has been made towards design and engineering design. Since CD-1 prototyping and testing of components and material, as well as selection of designs and detector components has started. The selection of the radiator for the shower max and quartz detectors is expected soon. The complete geometry of the pion detector is needed for completion of the tracking system.

Comments

- With the detector systems now moving into prototyping and testing, supplemental documentation on the specific goals of prototypes and tests, and results of detector components would be helpful towards CD2/3. As an example, the linearity of the PMTs is essential for the experiment and documentation of the impact of radiation on PMT performance and lifetime may be beneficial.
- The committee suggests to ensure availability, and if necessary, the design, of the necessary tools for survey and alignment for the measurement of alignment tolerances as required by the Project
- The committee suggests to complete the design of the pion detector geometry expediently as it impacts the design of the overall tracking detector system

- As no scope contingency is possible with the non-DOE awards, the committee suggests to re-evaluate the risk of the detectors not being ready, and, if necessary, implement tools to closely monitor progress and prioritizations
- Covid-19 related supply chain delays may impact the detector procurements. The committee suggests to study which components are most likely to be impacted by supply chain delays and re-evaluate the impact on each component and attempt to obtain approval for early procurement.

Recommendations

- The project should finalize alignment tolerances and establish a QA program to ensure the tolerances are met throughout installation of the detectors and the highly-correlated spectrometer collimators and magnets.

SC-5 DAQ and Electronics

Committee Members: Chris Cuevas

Findings:

- 60% design review held on 2021-March-18 was very useful and identified a few critical changes necessary for the Trigger Interface section.
- Prototype order for integrating ADC electronics including preamplifiers has been placed.
- Overall grounding scheme has been considered and a working group created to follow up on grounding issues and overall conformance to the work plan.
- JLAB DAQ 'VXS' boards have been identified and will be used to demonstrate integrating electronics with CODA
- Significant firmware development is in progress with new personnel to create required code and testing procedures.
- Reuse of firmware for GEM/APV25/MPD readout and control from the SBS subsystems will save significant development time.
- The information presented at the top level for the MOLLER project detector electronic subsystem for both the counting mode and integrating mode hardware shows a significant level of detailed work since CD-1. The overall deliverables table for the detector electronics including Key Performance Parameters [KPP] were very clear and the electronics/DAQ subsystems have been reviewed at the 60% level in 2021-March. Plans for a 90% review of electronics and DAQ in 2022-April are noted and will take place well before CD2/3.

- The advanced stage of an electronics and DAQ requirements document was presented and the collaboration of TRIUMF, JLAB and University groups demonstrates a strong team.

- The custom 16-channel ADC for the integrating electronics is fully designed and has been reviewed extensively with the Jefferson Lab FEE/DAQ team and prototype units are in production.

Comments

- Delivery for electronic components has been considered and reflected in the schedule and captured as a delivery risk. Critical components should be ordered as soon as possible after designs are approved to mitigate supply chain risks.
- Adding additional circuit board assemblies to the final order quantity to overcome yield issues should be considered in procurement plans.
- Presentation on HV Monolithic Active Pixel Sensors (CFI scope) including details for the 7 chip flexprint strips to the PMTs was more than adequate for this level of the design stage. Readout data transfer is planned with the CERN Giga-Bit-Transceivers and delivery delays will need to be considered in order to meet the Project installation schedule.
- Considerations for testing extra 25% length increase to HDMI cables from APV25 converter chips is a very good plan and should be completed as planned.
- Infrastructure and simulations for radiation measurements to verify levels within the limits of electronics in the shielding huts were presented and shows significant progress. Final results of simulations should be presented as part of the 90% design review.

Recommendations

- None

MOLLER Director's Review Committee

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Appendix

Suggestions to Improve Presentations and Documentation in Preparation for the CD-2/3 Review

- In the project overview talk, it would be useful to include a few pieces of high-level information which were not presented until the cost and schedule talks in this review:
    - Project point estimate and cost range
    - Critical path
    - Top-level breakdown of costs, e.g. primary cost driver(s)
- The ES&H talk needs to be expanded, and clarified in specific aspects
    - Key message should be that safety is central at JLab, and for MOLLER, and ES&H is tightly integrated with the project team and all of the work
    - Including some details about integration of the safety officer into the project team would be helpful
    - To the non-JLab reviewer, reference to the electrical safety changes was somewhat vague – consider more detail of the impact for MOLLER
    - The ePAS system explanation was not clear. This needs to be explained crisply with respect to what it covers and what it will mean for the project. If this is the system to define work, identify hazards and mitigations, a "worked example" may be a good way to explain this? Certainly the message that needs to be conveyed however is that the MOLLER project has an ES&H officer who is keeping up to date with the coming changes and will guide the project through.
- ES&H could also be incorporated (mentioned) in more of the technical talks where specific (unique) risks have been identified.