Closeout Presentation

2019 Director's Review of MOLLER

April 24-26, 2019

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Executive Summary

The MOLLER experiment at JLab proposes to measure the weak mixing angle, $\sin^2\theta_W$, to unprecedented precision at an energy that is intermediate between very low energies and the Z pole, 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 DOE Nuclear Physics program and represents a more than 4-fold improvement over the last measurement made in E158. Mission need was recognized in 2016 and the motivation remains strong through today.

Due to budgetary constraints, the Moller experiment was 'frozen' shortly after CD-0 was granted in December 2016. With a positive outlook in the FY20 PBR, the JLab Director requested an independent review of the recently formed project to assess the readiness to proceed with the planning for CD-1 approval. A Project Team was put in place and integrated into the scientific collaboration starting in December 2018.

The Project Team is to be commended for the enormous progress that has been made over a very short four-month interval since inception. The team consists of a strong balance of individuals with prior management and technical experience. There is an active and close interaction between the Project and the Collaboration with many members serving dual roles in the two structures.

The emphasis of the collaboration over the last couple of years has been on understanding how to overcome key technical challenges, assess the risks to the ultimate physics program, and optimize the technical down-selects to maximize the physics potential. The resulting pre-conceptual design looks robust and is ready to be taken to the next level.

While there is still substantial work to be completed prior to be ready for a CD-1 review, the Committee finds the maturity of the proposal to be appropriate for this stage of the project. The Project has laid a good foundation based on best project management principles and is ready to proceed to the next stage. We encourage the Project to work with the Laboratory and the funding agency to obtain the support needed to expeditiously finalize the conceptual design, develop a defensible cost range, and produce the deliverables required for a CD-1 review.

Answers to Charge Questions

1. Are the scientific and technical requirements clearly identified? Is the MOLLER conceptual design sound, achievable and sufficiently defined to meet those requirements?

Yes. Technical requirements are traced directly to physics goals. The requirements are incremental improvements to verified achievements.

2. Have all technical risks been identified, and are there appropriate plans in place to mitigate these risks?

Qualified Yes. A preliminary risk assessment was presented, however a systematic and comprehensive risk assessment needs to be completed.

3. Are the costs well-understood and properly estimated? Is the basis of the contingency estimate well founded, and is there appropriate cost and schedule contingency included to address the identified risks?

Technical:

No. We have not been provided with sufficient documentation to evaluate the costs. The project team will need to develop backup information in preparation for the CD1 review.

Project Management:

No. At this stage, it is difficult for the review team to assess if the costs are well-understood and properly estimated since the estimates have not yet been documented. The proposed approach to developing an estimate uncertainty is consistent with standard practices. A risk registry has been initiated but it has not yet been converted into a quantitative prediction of potential cost and schedule impacts.

4. Has all off-project scope that is required for the successful operation of the MOLLER experiment been identified? Are credible plans in place to secure completion of that scope?

Yes. The identification of off-project scope and the plans to secure completion of that scope is appropriately mature for this stage of the project.

5. Is the plan for Project management well-founded and appropriate for this scale of project?

Yes. The Project management plan is sound and best practice principles are being implemented. Although there is still much work to be done for CD-1, the project management team has made enormous progress in the first four months since it was created.

6. Are ES&H aspects being properly addressed for the Project's current stage of development?

Yes.

7. Has the project team responded appropriately to recommendations from prior Director's Reviews?

Technical recommendations:

Qualified Yes. There exists short responses to each recommendation, however links to other explanatory documents should be added. There remain numerous open recommendations with plans to close them on an appropriate time scale. Responses should be tracked along with the recommendation.

Project Management recommendations:

No. The project team recognizes that there are still numerous recommendations from past reviews yet to be addressed in order to be prepared for a CD-1 review.

ES&H recommendations:

Yes.

1.0 Project Management

Committee Members: Ed O'Brien, Chris Polly

Findings

- The MOLLER experiment received CD-0 approval in December 2016 but has been 'frozen' since January 2017.
- JLab Management formed a MOLLER Project Management team in December 2018.
- The Project team leads an organization that includes Control Account Managers and Experiment Contacts, supported by a group of JLab technical advisers and reviewers. A total of 35-40 people make up the MOLLER team.
- The current schedule has MOLLER CD-1 approval in 3QFY20, CD-2/3A approval in 1QFY21, CD-3 approval in 2QFY22 and CD-4 approval 4QFY25. On this schedule the experiment would take first beam 1QFY25.
- The Project team has created a Resource-Loaded Schedule that has a critical path that goes through the design, fabrication, installation and testing of the toroid.
- The RLS information has been used to create a technically-driven cost and obligation profile.
- There is a project labor profile that has an integral of 60-65 FTEs covering a period of 3QFY19 to 4QFY25.
- The FY20 President's Budget Request contains a line for MOLLER with a CD-0 cost range of $25-35M.
- The project management team has carried out a bottom-up cost estimate in early 2019. The result of the estimate was a Total Project Cost for MOLLER of $38.4M

including 40% contingency on all items except project management that carries no additional contingency.
- The project is 45% labor, 55% M&S.
- There is no bottom-up contingency estimate for the project.
- MOLLER has a preliminary Risk Registry, preliminary Conceptual Design Report and preliminary Hazard Assessment.
- MOLLER collaborators at JLab and elsewhere have carried out pre-conceptual design and R&D work for some time. No Other Project Cost (OPC) work has started.
- The Project has captured the multiple reviews required from design to commissioning that will be needed. These reviews are included in the WBS line items.

Comments

- The MOLLER Project team has been staffed and trained quickly. They have been very productive since they formed four months ago.
- The team is a good mix of experienced project managers, CAMs and technical experts along with personnel new to managing DOE projects.
- JLab has been very supportive of the MOLLER project. Both the project team and scientific collaboration are enthusiastic about bringing the project to fruition.
- The project assumptions and dependencies are broadly considered and achievable. However, at this early stage in the project it was not possible to tell whether the list of dependencies was complete.
- The Project team needs to come to an agreement with DOE and JLab on a conceptual design and R&D plan soon. They need to establish an OPC/CDR budget for FY19/FY20 and start on the conceptual design and R&D work as soon as possible. It will take many months for the conceptual design to reach a maturity level sufficient for a successful CD-1 review.
- The Project team needs to come to an agreement with JLab Management and the DOE Program Office on how MOLLER is to be managed in the context of the August 2018 memo from Steve Binkley on the managing of DOE MIE projects with TPC's of $50M or less through the use of a tailored approach to 413.3B regulations.
- The RLS contains a very limited plan for conceptual design and safety reviews of the Level-2 systems between now and CD-1.
- There has been a good start on a few project documents required for CD-1 such as the Preliminary Hazard Analysis Assessment, WBS Dictionary and Risk Registry. A number of key CD-1 documents have not been started or have barely begun such as the Basis of Estimate documents, preliminary Project Execution Plan (or Project Management Plan depending on DOE Program Office guidance), Conceptual Design Report, Acquisition Strategy and Analysis of Alternatives.
- It was not possible to assess the validity of the cost or schedule estimate without back-up documentation. Basis of Estimate documents are needed.

- The amount of work completed by the project over such a short period of time (<4 months) is commendable and lends confidence in the ability of the team to produce the deliverables required for CD-1.
- The review committee agrees with the project's assessment that three of the project management related recommendations from the 2016 review can be closed (2016 Dec DR.05.R-08, 2016 Dec DR.05.R-09, and 2016 Dec DR.05.R-10).
- The project relies on important contributions from many institutions. The responsibility of each institutions should be captured and formally documented.
- Healthy progress has been made on the remaining, comprehensive set of project management recommendations from the 2016 review. To avoid duplication, this committee will not repeat those recommendations, but reiterates the importance of satisfying those recommendations prior to seeking CD-1.
- The estimated resources for the management of the project look insufficient. In particular, the effort required from an L2/CAM position for control accounts of this scale is likely to be 0.5 FTE or larger, while the project manager is minimally 0.75 FTE. A deputy PM who also serves the role of risk manager would be hard-pressed to fulfill their responsibilities at 0.5 FTE.
- It is hard to justify the 0% estimate uncertainty assessed on the project management.

Recommendations

1. The Project team should come to an agreement with JLab Management and DOE-ONP on the scope and budget of OPC and CDR activities for MOLLER in FY19 and FY20. The project should base the scope and budget on an evaluation of the resources required to finalize the conceptual design, produce a reliable cost range, and provide the remaining deliverables needed for CD-1.
2. The Project team should come to an agreement with JLab Management and DOE-ONP on the management approach for MOLLER in light of the August 2018 DOE memo on management of DOE MIE projects with TPC's of $50M or less.
3. Basis of Estimate documents in support of the MOLLER cost and schedule estimates should be developed as soon as possible. After establishing a complete set of Basis of Estimates and the documentation supporting those estimates, the project and laboratory should conduct an independent cost review to assess the validity of the cost range.
4. The Project team should schedule a cost, schedule and technical review for each Level-2 system with the goal of validating the information in the RLS and helping to support the cost estimate. The review committees can be internal.
5. The project should utilize the risk registry to produce a quantitative assessment of the total cost and schedule risk. This assessment can be used to help establish a reliable cost range and ensure key milestones have sufficient float.

2.0 Magnet

Committee Members: David Harding

Findings

- The MOLLER experiment relies on two air-core toroidal magnets with seven coils each. The upstream magnet uses relatively simple rectangular coils, while the downstream magnet has a much more complicated shape with multiple loops to generate the required magnetic field.
- The collaboration has done (and continues to do) extensive magnetic modeling of the spectrometer, feeding magnet models into physics assessments, to evaluate the impact of misplaced conductors on the physics measurements.
- A model coil has been designed in consultation with a coil vendor, fabricated by the vendor, and tested by the collaboration.
- The hybrid coil design has received most attention to date, but a segmented coil configuration is also being evaluated.
- The collaboration has developed conceptual models of the support structures, which still need engineering design.
- The collaboration's judgment is that the magnetic field map generated by modeling, supplemented by data from tracking measurements, will be sufficient, and that a detailed measurement of the magnetic field in not needed.
- The baseline design calls for the toroid magnets to be housed in a vacuum vessel that would both eliminate multiple scattering of the electron between target and detector and provide clean transport of the unscattered electron beam to the dump. An alternate design is being evaluated that replaces the vacuum with ~99% helium gas at air pressure except for a central vacuum tube for the unscattered beam.

Comments

- The initial conductor placement tolerances that the collaboration has determined to be completely acceptable will be readily achievable. The coil package dimensions, driven by aperture considerations, are tighter than the conductor tolerances, but still readily achievable by a competent coil fabricator.
- The model coil was designed to primarily address the thermal issues of a conductor current density well above levels typical of water-cooled electromagnets. The measured power consumption, water flow, and attendant temperature rise matched several independent calculations. The generated magnetic field also matched calculations. Neither of these results is surprising.
- The model magnet was insulated with pre-impregnated fiberglass tape to minimize cost, but that left unanswered mechanical stability issues of a fully vacuum impregnated coil.
- The segmented coil and the hybrid coil appear to both be viable. Coil winding for the segmented coil appears easier, but establishing and maintaining the alignment

may be more difficult. The vendor of the model hybrid coil suggested that cost would be similar.

- Given the high cost of the power supplies, it might be worth exploring whether additional copper could be squeezed into the volume on the outer legs, reducing the total coil resistance. Savings would come in power supply costs, cooling water needs, operating costs, and temperature gradients in the coils.
- Given the high temperature rise of the water through the coils, and thus the severe temperature gradients from one layer to the next within the coil, the stresses on the epoxy insulation and the impact on coil deformation from differential expansion need to be evaluated.
- Since the entire wedge determined by the coil profile is available for support, it should be possible to design an adequate structure to maintain the coil geometry and position during operation, but a thorough FEA model, including gravity, Lorentz forces, and thermal stresses will be necessary to ensure success.
- Initial alignment of the toroid coils and verification over time must be planned from the early stages, with appropriate features built into the coils and access ports in the containing vessel.
- The reduced cost of a vessel that does not need to withstand the forces of atmospheric pressure against a vacuum seems attractive, but the idea is young enough that the full implications (plus and minus) are not yet understood. There is said to be no impact on the asymmetry measurement from having the electrons pass through helium rather than vacuum, but the collaboration is assessing the impact of the additional material of the beam pipe in the central region. The risk of potential catastrophic impact on the experiment's phototubes due to even a small helium leak must be acknowledged and mitigated adequately.
- The collimator designs are well advanced and tightly coupled to the physics needs and the detector protection.
- Significant effort has been devoted to the cost estimate, but the committee did not see enough details to assess its validity.

Recommendations

6. Complete and document the engineering analysis and cost estimates of the coil options. Commit to one design.
7. Complete and document the engineering analysis and cost estimates of the vacuum vs. helium gas choice, weighing the risks to other parts of the apparatus. Commit to one design.

3.0 Target

Committee Members: Kelly Dixon

Findings

- The team that will design target system previously had responsibility for the Qweak target.

- Conceptual design of the vacuum system and CFD model are both in progress. All other systems have not been started. The use of the Qweak liquid pump and heat exchanger is being evaluated.
- The target conceptual design, along with many other facets of this project, is currently funded outside of the project.
- The target is being designed to take the full heat load of the beam, pump and heater.
- A high level schedule, a summarized component cost estimate, and labor profiles were provided.
- Cryo specs: 4 kW load, 15K inlet temp and 13 atm dP
- No new cryogenic transfer lines are required.
- Newly shortened 125 cm target should be simpler than the Qweak target was to design.
- Target group has resource-loaded schedules. This effort will consume 50% of the Target group's time.
- Two other targets that could compete for resources are the polarized and unpolarized CLAS12 targets. For the present schedules, the first target should already be taking beam during the design phase of the MOLLER target and the second CLAS12 target should not be a large effort and doesn't require a highly specialized design.
- There is no anticipated need to access the LH2 target after shielding has been installed due to a proven design, leak checks, and redundant temperature sensors.
- Existing Qweak pump is a modified truck turbine and would provide about half the flow needed for MOLLER. They may use this pump but would need to be concerned with cavitation and head loss. An available pump from Barber-Nichols could be available in less than 12 months. A similar model (1.8 kg/s) designed by Cal Tech exists at SLAC.
- Expected cryogenic helium is expected to enter at 12K @ 14 atm and leave at 19K @ 4 atm.
- They will require a large line to vent H2 outside of the Hall during upsets.
- Recommendations from the previous reviews concerning the target have largely gone unaddressed (dispositions later provided in a tracker):
    - Specify the number, location, and beam current requirements for all solid targets.
    - Calculate the radiation load on nearby scattering chamber components for the purposes of estimating the O-ring and vacuum pump and gauge lifetimes.
    - It will be important to assess the effect of irradiated beamline components on the plans to move the experiment in and out of the beamline.
    - The cost-benefit analysis results were provided assessing the use of the E158 scattering chamber and they claim this to be closed, all other recommendations are still open.

Comments

- Continue to complete previous recommendations from past reviews. Building a new version of the target scattering chamber sounds reasonable but needs a more quantitative analysis and any available documentation to support this direction.
- The LH_2 target is a sophisticated system whose operation is critical to the success of MOLLER. The JLAB target group has extensive experience in the manufacture, implementation, and operation of high-power cryogenic targets. While the committee has confidence that the group can provide a target to spec, this is a critical component for MOLLER and additional supporting documentation will be required for CD1.
- The direction of using the existing Qweak heat exchanger pump and heat exchanger is confusing and needs further clarification or consistency. We were told in the plenary session that these would be adapted but were later shown in the breakout session that this is still undecided.
- The risk management was only confined to problems that can arise after construction and check out. This should be expanded to include: material/equipment procurements, various design and fabrication errors, transportation of sensitive items, maintaining staffing resources, etc.
- Previous CFD simulations appear to have good correlation with actual data as presented. This looks very encouraging as is important to the success of this project.

Recommendations

- None.

4.0 Detector

Committee Members: Liping Gan, Elton Smith

Findings

- The institutions and personnel that are responsible for each detector sub-system have been clearly identified. A task tracking mechanics is established.
- The technical comments and recommendations from the previous Director's Review are still valid and addressing these issues are important to ensure the success of this project. Out of 25 technical comments and recommendations from the 2016 review, 3 of them have been resolved. The collaboration should continue its effort to address the remaining items timely.
- The experiment will run in two modes: integrating (production) and tracking (counting). The detector technologies are well motivated by the requirements and based on previous experiments.
- In the production mode, two detectors play a principal role: 224 thin quartz Cerenkov crystals and 28 shower-max (quartz and tungsten sandwich). Each are coupled to a photomultiplier via an air light guide. The photomultiplier base is able to switch between integrating and counting modes. Multiple prototypes of

these detectors have been tested with beam between 2013 and 2018. The designs of the detector itself, base and pre-amplifiers are almost complete; the ADC electronics needs additional work.

- The tracking system consists of a GEM tracker and pion detectors in addition to the Cerenkov detectors operated in counting mode. Tracking data is taken to determine the kinematic factors in the asymmetry, check optics, and determine pion backgrounds. Data in this mode will be taken at low luminosity about once per month.
- Detector and electronic elements are being assessed for radiation hardness using the low-energy electron accelerator at Idaho State University (ISU).
- The full detector Monte Carlo simulation contains the main elements of the detector in the area of the spectrometer. Significant progresses have been made to implement some of the realistic beam line material in the simulation package. However, it still lacks the following elements: Detailed central beam pipe design from the target to the dump (He option), fringe fields down to R=0cm and updated fields for misaligned magnets, small angle monitors, detector quartz, light guides and PMTs, and support structures.
- The experiment Figure of Merit (FOM) is dependent on the electron beam energy and running time must be compensated if the accelerator is not able to deliver 11 GeV to Hall A. In addition, the collimators are designed for a specific beam energy and would need modifications for a lower beam energy.
- Improvements in the polarimetry will be accomplished off-project as a dependency as these updates are also required for other experiments.

Comments

- Potential backgrounds produced from the photon blocker (collimator 5) should be carefully examined and its impact on the detectors and electronics should be checked.
- All proposed sub-detector systems look feasible. No obvious show-stoppings are identified.
- The experimental requirements should be explicitly defined. For example, in Table 4 of Pre-CDR, the detector "non-linearity (goal) $5x10^{-4}$" is confusing. Further clarification suggested that the actual requirement for the detector non-linearity is better than $(1\% \pm 0.1\%)$.
- As part of their schedule optimization, the collaboration should identify which sub-detector systems are essential for the early phase of the experiment.
- It is encouraging that the collaboration aims at a full estimation of the radiation dose on the primary detector assembly and associated electronics to be carried out before end of 2019.
- The GEM detectors will require a support and motion system of non-negligible complexity. It is important that a design of sufficient maturity to allow a credible cost estimate be developed before the next review.
- The collaboration has been testing the radiation hardness of the detector components in a low-energy electron facility. Experimental investigations of the effects of radiation are valuable inputs to the evaluation of technical choices. However, much of the damage to electronics and detectors is due to damage from

hadrons (neutrons in particular), not electromagnetic radiation. Therefore, irradiation from low energy electron beams alone should be complemented with measurements with neutron sources. JLab has a calibrated neutron source, which could be used for such studies.

- The missing items in the simulation are needed to assess backgrounds behind the spectrometer and finalize design. The estimated radiation dose to integrating detectors and preamps may be affected by these additions of these elements to the simulation.
- The collaboration is investigating the effects of background backscattering from the downstream alcove and beam dump. We encourage them to continue to assess the impact of these backgrounds as the simulation includes more details.

Recommendations

8. Complete the inclusion of the detailed detector geometry into the detector simulation to confirm design choices, and verify that the final design meets the requirements of the experiment.

5.0 Electronics

Committee Members: Sergio Zimmermann

Findings

- The Electronics System will use already existing electronics or upgrades to existing electronics.
- The MOLLER detector system operates in two modes: tracking mode and integrating mode.
- The PMTs will be in place for these two modes, while the GEMs are used just in the tracking mode. The PMT base has a relay that routes the output to two different pieces of electronics, one is designed for tracking and the other for integrating.
- The PMT base is part of the PMT detector system. The proposal for grounding is to have the entire electronics chain grounded via the PMT HV and have separate voltage regulators on each component, supplied by ground isolated PS.
- The GEM detectors will use the same readout IC used in the SBS experiment.
- The Trigger and Trigger Supervisor were not discussed in details.
- A list of required electronics for each operating mode (tracking or integrating) was presented.
- In the Technical Homework session, the strategy to estimate the radiation on the electronics was presented and includes the following statement: “A full estimation of the radiation dose on the primary detector assembly and associated electronics should be achievable before end of 2019.”
- The Risk Assessment document lists 2 risks associated with electronics, and both refer to additional effort to complete the design.

Comments

- It is a good strategy to use as much as reasonable electronics already developed for other experiments or to implement minor/small modifications if needed. It reduces costs and risks, and allows for reuse of parts of firmware and software.
- To have the PMT electronics independently grounded on the detector side for every signal path requires ground isolation on every component (e.g., electronics input amplifier, ADCs, etc.) Probably the ground should be grouped on signals going to one ADC board and the cables routed on the same bundle.
- The Electronics team should use the estimation of the radiation type and dose to assess possible damage or single event upset on the front-end electronics. The team has to understand these effects and plan to mitigate them. Observe that a lot of information is available in the literature and from result of previous tests.
- There are more risks in electronics in addition to just associate with effort during design. For example, there are risks of electrical or magnetic interference and ground loops when the whole system is installed, component availability and quality during production, etc. The team will profit from an overall risk analysis that includes all these risks (for design, production and installation) and envisions mitigating strategies.

Recommendations

9. Prepare a plan to handle possible radiation damage to the front end electronics, pending the results of the radiation field estimates.

6.0 Integration/Infrastructure

Committee Members: John Hogan

Findings

- PM has sound integrated approach to integrate lab resources building on previous institutional project (12GeV, SBS) experiences as the reference for the MOLLER PMP.
- All collaborators have been identified and a plan is being developed to establish contractual agreements to include roles and responsibilities specific to each University.
- The Infrastructure and integration CAM has identified required interfaces at level-3 for all the subsystems.
- Several of the subsystem CAM's have identified technical interfaces and infrastructure space allocation requirements needed to support their scope of work.
- All Hall-A required infrastructure and utilities (Space, Cryogenics, Gas, Power, Shielding, etc.) has been identified along with a plan to integrate the MOLLER apparatus into the current planned experimental schedule.

Comments

- It would be beneficial to the project to include time requirements (durations) on the workspace allocation tables.
- The project planning would benefit from including expected dates for completing designs, holding reviews and delivery of subsystem components (on and off project).
- A deliberate plan should be in place to evaluate/verify the expected deflection of the floor once the shielding is in place to ensure the target support/alignment design is adequate.

Recommendations

- None.

7.0 Safety

Committee Members: Paul Collins

Findings

- The Project documentation is appropriate for the stage of the project. The Project is working to established Jefferson Lab ESH&Q processes. These programs are mature and have a solid history of success. The Draft PHA is nearly complete. Hazards are well understood and are consistent with current lab identified hazards. The realization of human error's influence on project success has also been recognized.
- The scope of the project has been defined and risks are being captured and managed as part of the risk registry.
- Lessons learned from the 12GeV Upgrade and other past projects have been incorporated

Comments

- The Project documents are in various states of readiness and need to be finalized. These documents provide the framework for successful management of the ESH&Q aspects of the project. Confirmation that the current Environmental Assessment covers the activities and impacts, needs to be completed before CD-1.
- Scaling the dollar threshold, when assessing risk, to the project is commendable. There may be benefit to the Project to evaluate scaling for schedule impacts as well.
- The following recommendations have been addressed:

  2016 Dec DR.05.R-12: Start developing the complete set of project documents for CD1, such as the Project Execution Plan, the risk management plan, Hazard Assessment (HA), etc.

2016 Dec DR.05.R-16: Project should develop QA guidelines in similar fashion to the existing ES&H guidelines.

Recommendations

10. Finalize the Preliminary Hazard Assessment
11. Document that the current Environmental Assessment covers the MOLLER activities and impact (NEPA document).

8.0 S&T Requirements

Committee Members: Geoff Greene

Findings

- The MOLLER experiment seeks to measure the Weak Charge of the electron, Q_W^e by elastic e-e scattering at 11GeV. Electron-electron scattering provides one of the most "pristine" laboratories in which to study the fundamental Electro-Weak interaction. MOLLER can be interpreted as a determination of the weak mixing angle, $\sin^2\theta_W$. MOLLER's goal of a precision of 0.1% is at a level that is competitive with measurements at the Z pole and is more accurate than off pole measurements. MOLLER is the only experiment that can attain this accuracy in the e-e system and its reach is unlikely to be exceeded until the advent of a new lepton collider.
- Consistency between the MOLLER result, at the projected sensitivity, and the Standard Model prediction can be interpreted as a test of non-standard interactions at a mass scale of 27TeV, an energy scale that is beyond the reach of any other leptonic experiment.
- When it reaches its design goal, MOLLER will reach a sensitivity equal the previous best e-e PNC experiment (SLAC E158) in 9 days of running. The MOLLER collaboration proposes a data run with a total running time of ~1 live year.
- Recognizing that the e-e scattering involves identical particles, the MOLLER collaboration has developed a novel seven-coil spectrometer that allows 100% event acceptance with only 50% geometrical acceptance. This geometry allows for a very compact spectrometer with a very favorable signal to background.
- While MOLLER will require control of systematic effects at a level that is more demanding than the current state of the art (as demonstrated in previous electron scattering PNC experiments such as $Q_{weak,}$ E158, etc.), the required improvements appear to incremental in nature.

Comments

- The collaboration is to be commended for the clever spectrometer design. The concept of a spectrometer with 50% geometrical acceptance but 100% event acceptance is elegant and unexpected.
- MOLLER offers an extremely important opportunity to make a clearly interpretable fundamental measurement. MOLLER is additionally attractive because of the robustness of the Standard Model prediction in the purely leptonic sector. The gain of x5 over the sensitivity over the best previous e-e PNC measurement (E158 at SLAC) is important and any compromise in the MOLLER design that degrades the sensitivity by a non-negligible amount must examined with great care. MOLLER should either be done well, or not at all.
- The MOLLER Collaboration has provided strategies for the incremental reduction of systematic uncertainties that appear plausible. While some of these have been documented in technical reports, it would be desirable to address them all in a reviewable document. Such a document would be particularly useful at the time of a CD-1 review.
- The MOLLER team has vast experience in precision PNC electron scattering. The committee believes that collaboration contains expertise in all technical areas required for MOLLER. The collaboration appears to have sufficient scientific manpower to support the MOLLER project but it would be helpful at the next review to explicitly identify the anticipated level of effort of "off-project" scientific personnel.
- The optimization of the MOLLER design and its scientific reach are dependent on the accelerator energy. It is important to understand this dependency.

Recommendations

12. An analysis of the MOLLER design optimization as a function of beam energy should be carried out. This should be done as soon as possible so that MOLLER will be prepared to respond should the expectation of out-year accelerator performance change.