Presentations for this review of the MOLLER experiment and project were conducted on December 12-13, 2019 at Jlab. The committee members for this review were:

Tim Michalski, Jlab
Dave Mack, Jlab
Matthew Poelker, Jlab
Mike Snow, Indiana University (chair)
Timothy Whitlatch, Jlab

The charge to the committee was as follows:

“In support of the upcoming Critical Decision-1 (CD-1) reviews, we request the review committee to assess the readiness of the Conceptual Design and the Conceptual Design Report that have been developed by the MOLLER team in preparation for CD-1. In particular, we request that the review committee address the following charge questions:

1. Are all of the performance requirements that are necessary for achieving the scientific goals of the experiment identified and documented in the Conceptual Design Report (CDR)?

2. Does the conceptual design satisfy the performance requirements of the experiment?

3. Are the technical specifications that drive the Conceptual Design defined clearly, and are the specifications directly motivated by the performance requirements?

4. Does the Conceptual Design represent a feasible and efficient approach for achieving the scientific goals?

5. Are the specifications sufficiently complete to guide development of the Conceptual Design into a Final Design that satisfies the requirements?

6. Have remaining required technical studies necessary to resolve risks and technology choices been identified?

7. Has the project responded satisfactorily to the technical recommendations from previous reviews?

This report is organized as follows. We first present the recommendations upon which the responses to the questions above are based. This is followed by the responses to the charge questions. We then present the comments and findings. The report ends with a chronological description of the review process.

Based on the responses of the MOLLER collaboration to the pre-review questions, to the additional questions generated in the course of discussions on the second day of the review, after some committee discussions with Thia Keppel regarding the form which the committee's responses should take, and after some further consideration of the MOLLER responses to the homework questions in the weeks after the review, the committee provides the following recommendations and responses to the charge questions as follows:

Recommendations:

1. We recommend that MOLLER specify in one location the physics acceptance and collimation for the experiment.

2. We recommend that MOLLER formulate a plan to search for the possible sources of the inconsistency of the beam current monitors and continue to improve the noise performance of the beam current monitors.

3. We recommend that MOLLER simulate the single-sector and whole detector sensitivities for the existing design with the tolerances specified in the CDR.

4. We recommend that Jlab with input from MOLLER organize a preliminary liquid hydrogen target and associated shielding structure safety review for design input.

5. We recommend that MOLLER study in simulation the robustness of the background extraction procedure and MOLLER asymmetry with respect to hotspots, soft backgrounds, etc.

6. We recommend that MOLLER recheck and record their estimates of the sensitivity of the response of the different components of the detector signals to the raster motion.

Responses to Charge Questions:

1. Are all of the performance requirements that are necessary for achieving the scientific goals of the experiment identified and documented in the Conceptual Design Report (CDR)?

All known performance requirements are specified in the CDR except for one noted in the recommendations, the required accuracy of the beam current monitor charge asymmetries. The residual dispersion at the target, without which the energy sensitivity cannot meaningfully be determined, did not appear in the CDR but was closed at the April 2019 Director's Review.

2. Does the conceptual design satisfy the performance requirements of the experiment?

Yes, if the concerns raised in the recommendations above and comments below are addressed. Note however that some of the designs presented in the CDR are notional (two-bounce collimation, beamline windows, etc.) and will require more work in preparation for CD2.

3. Are the technical specifications that drive the Conceptual Design defined clearly, and are the specifications directly motivated by the performance requirements?

Many technical specifications are defined clearly, however we found that the collimation and shielding specifications need to be better described and defined, along with some other specifications discussed in the recommendations and comments in this report. The specifications are directly motivated by the performance requirements.

4. Does the Conceptual Design represent a feasible and efficient approach for achieving the scientific goals?

Yes. However the points brought up in some of the recommendations (which were not addressed in the CDR) represent potentially serious challenges to the stated scientific goal of improving the existing uncertainty in the Moller asymmetry at this Q^2 by a factor of 5.

5. Are the specifications sufficiently complete to guide development of the Conceptual Design into a Final Design that satisfies the requirements?

We recommend that MOLLER specify in one location the physics acceptance and collimation for the experiment.

We recommend that Jlab with input from MOLLER organize a preliminary liquid hydrogen target and associated shielding structure safety review for design input.

6. Have remaining required technical studies necessary to resolve risks and technology choices been identified?

We recommend that MOLLER formulate a plan to search for the possible sources of the inconsistency of the beam current monitors and continue to improve the noise performance of the beam current monitors.

We recommend that MOLLER study in simulation the robustness of the background extraction procedure and Moller asymmetry with respect to hotspots, soft backgrounds, etc.

We recommend that MOLLER simulate the single-sector and whole detector sensitivities for the existing design with the tolerances specified in the CDR.

We recommend that MOLLER inspect and record their estimates of the sensitivity of the response of the different components of the detector signals to the raster motion.

7. Has the project responded satisfactorily to the technical recommendations from previous reviews?

The collaboration has closed some of the technical recommendations and is working on the remainder. However not all of these remaining issues were presented to this committee, and some might be important for CD1.

In addition to these responses to the charge questions and the recommendations, the committee makes the following comments and findings for the consideration of the MOLLER collaboration:

COMMENTS:

(1) CDR updates: Independent of whether or not the "official" version of the CDR can be updated according to the DOE rules, we request MOLLER to update key items in their internal collaboration CDR to reflect the various inputs from the discussion at the review.

(2) TOSCA modeling - For parts of the acceptance where electrons pass within 1-2 cm of the torus conductors, the effect of the cooling water holes in the conductor may not be negligible. Given the tight clearances, it is critical that the beam envelope leaving the upstream torus and drifting to the downstream torus be modeled with mm scale accuracy. To see if near-field effects could be an issue, at some fixed current one could compare the magnetic fields from a 1 m long piece of conductor with and without the cooling water hole.

(3) Air light-guide passivation – The multiple MOLLER detector groups using air light-guides should investigate whether a passivating gas flow is needed to prevent corrosion of the internal mirror finish. If required, it could become a significant effort for the main, thin detector.

(4) Rad hardness - The detector groups have a specification for rad-hardness, but it's probably worth emphasizing they need to certify everything that goes into the detector so there will be fewer surprises. For example, not all "quartz" is created equal, and thus they will need to communicate with the PMT vendor to ensure that the windows are of an appropriately rad-hard brand like Spectrosil 2000. And we do mean certify "everything": In Qweak, the first generation of BNC connectors in the lumi bases saw their dielectrics turned into the consistency of toothpaste. Associated corrosion of the BNC connector effectively turned it into a battery causing a significant ADC pedestal shift which was how the problem was identified.

(5) Shielding - When shielding detectors and electronics, the collaboration should keep in mind that line of sight shielding is important but may not be sufficient due to air glow. The dose inside the conceptual electronics bunker will likely be dominated by the open doorway even though the bunker is located at large angles and the doorway faces a supposedly quiet direction. The dose inside a shielded box containing preamplifiers can easily be dominated by the holes needed for cables and air flow.

(6) Beam halo backgrounds – We did not flag this in any recommendations because there appears to be a clear strategy for dealing with it as long as the dilution is not larger than it was in Qweak. Firstly, the background will be monitored by the ring 1 detectors as well as diffuse scattering detectors at large angles. Secondly, if the dilution from this background is only O(0.1)%, then an O(1) ppm asymmetry from this source would be an O(1) ppb level correction with an optimistically acceptable O(0.1)ppb uncertainty, similar to the case for the pion background. Finally, the collaboration has the option of increasing the frequency of HWP reversals to better cancel this mechanical asymmetry (although this means coordinating the starting and stopping of runs between the 2 or 3 halls that care about polarization).

(7) Metrology. The collaboration should consider ways to improve the confidence of measurements of the distance between the downstream target window and collimator 2. The sensitivity to this distance appears to be low for the uniquely forgiving kinematics of the Moeller channel, but it could be more important for the acceptance in other channels like e+p and e+Al elastics. In addition, the millimeter tolerances on the hybrid magnet seem aggressive.

(8) Adiabatic damping: A factor of 150 in helicity correlated position damping is extremely optimistic. Proper beam envelope matching across accelerating sections – which is a requirement for adiabatic damping - is certainly a reasonable expectation and something that accelerator physicists strive for. However in practice, achieving this goal is quite challenging, ostensibly because there are insufficient diagnostics in the machine (e.g., beam position monitors, some located at nodes instead of anti-nodes), particularly at the injector where the largest gains can be achieved**.** In addition, the instability of the beam tune can be detrimental to long-term gains.

We agree with MOLLER that the planned injector upgrade could help. The 200 kV photogun will make “stiffer” beam and there should be no x/y coupling inside the “booster” which will replace the ¼ cryomodule. And beam position monitors will be properly located at beam envelope anti-nodes. These improvements could make it easier to envelope-match.

If adiabatic damping at the injector turns out to be difficult, and the 150 times reduction in position asymmetries is not achieved, the MOLLER group has two fallback options. The RTP Pockel cell provides fast helicity flipping at ~ 2 kHz with very short settle time, and it has been demonstrated during PREx to provide very small position asymmetries directly at the photocathode, < 100 nm, roughly a factor of 10 smaller than observed during previous parity violation experiments at CEBAF. And the helicity magnets at the 5 MeV region of the injector demonstrated to be effective during QWeak are still installed, and could be operated using an automatic feedback loop.

(9) Transverse Polarization Control: Specify the feedback process for the transverse polarization tuning and its interaction with the accelerator. Precise calibration of the Wien filters will be necessary: spin direction versus applied B and E fields, in order to apply feedback “on the fly” without interrupting beam delivery to the halls. It remains to be seen if “on the fly” spin polarization feedback can be implemented.

After the review, the topic of transverse polarization and “unbalanced linacs” was discussed with the CEBAF Operations Department. Indeed, operators are aware that adjustments to linac energy gain can influence the direction of the spin polarization at the halls. So to avoid rotating the direction of the polarization at the halls, when the gradient in a poorly-performing cavity is de-rated to reduce trip rate, gradient is increased only in cavities within the same linac to compensate. In this sense, homework question #3 was ill posed. However, it is still worthwhile to imagine the process whereby transverse polarization is made to vary over time, particularly out-of-plane polarization. It is difficult to identify any mechanism by which out-of-plane polarization can be made to vary with time (i.e., drift).

(10) Downstream magnet (Hybrid) Fabrication: MOLLER presented an in-vacuum concept for the magnet held by a “strongback” mount. Although these concepts appear feasible, meeting the tight tolerances for fabrication and assembly/installation will take much thought and analysis. The magnet test component that was fabricated validated some aspects of the magnet design concept but not others, in particular no attempt at tolerance control was made, particularly as it relates to magnet position within an evacuated enclosure, following repeated venting and pump down. We assume that MOLLER will plan to fabricate various test pieces to prove different aspects of the design.

(11) Robustness in design – add as a “design consideration” – areas of very high radiation and activation should have very robust designs to avoid potential failures requiring access and preventing long cooldown/repair times.

(12) Redundancy in areas of high radiation should be considered to increase the probability of systems, such as diagnostics, continue to provide critical functions throughout the experimental runs. Diagnostics and instrumentation on magnets as an example.

(13) Collimation and Shielding. We appreciated seeing slide 18 from the spectrometer talk, showing the layout of the collimators, lintels, collars, etc. and partially addressing one of our initial questions. Although the slide omitted some important elements like the beam tubes, magnet coils, shielding, etc., it did indicate that there’s no direct line of sight from the detectors to the target. However it appears that the upstream end of beam collimator 1, the edges of collimators 2 & 4, and the lintels and collars are all in direct line-of-sight to the detector plane. These will glow like crazy, but are presumably in the existing simulations. It is worth considering whether or not it is possible to better shield at least the beam collimator, which receives around 4 kW of beam power, and appears from slide 18 of the presentation to be a 1-bounce background source.

The collaboration might consider developing fallback plans to better shield the detectors if it becomes necessary.

More generally, we feel that the collimation design deserves its own section in the CDR, where the function of each element can be described in the context of the other elements.

(15) Polarimetry. The polarimetry error budgets in the table in the CDR and in the review presentation did not explicitly list the error from the extrapolation from 2 uA to higher beam current. At the review it was stated that the 0.5% error quoted in previous parity violation measurements for this error can be much smaller in MOLLER. We ask MOLLER to quantify this expected extrapolation error and list it in the error table.

(16) Windows. Simulations should be done to estimate the secondary neutral and charged particle background (including hyperons) from the nearly 3 mm effective thickness (3% X0) downstream aluminum spectrometer window (see DS window report in Homework Report) just ~4m upstream of and in line-of-sight with the main detectors. Although clearly the scattered electron flux incident on this window is much smaller than that from the beam itself, the Lorentz boost ensures everything produced at this window including protons, neutrons, and pions from hyperon decay as well as any other process will probably hit the detectors. Simulations should be done to assess the impact of this source of background- they may help inform improvements to the experiment's design. Relying solely on the pion detectors to take care of the potentially large corrections from pions including those from hyperon decay seems risky since it means the design of the experiment is not being optimized to minimize this background.

According to slide 3 of R. Fair's spectrometer talk, there is a 1 mm thick aluminum window at the downstream end of the scattering chamber, which is presumably the "thin" window isolating the target vacuum from the spectrometer vacuum. This seems thick enough to perhaps withstand an atmosphere of differential pressure, instead of just the differential pressure between a good target vacuum and a poor spectrometer vacuum. If the detectors see this 1 mm thick aluminum window it would substantially increase the aluminum dilution of the signal as it is about 4 times the combined thickness of the target cell.

FINDINGS:

(1) Accelerator Physics Studies. One committee member was struck by the number of cases where the possible size of certain systematic effects associated with the propagation of some phase space property of the polarized beam through the accelerator were roughly estimated but not quantified, by the evidence of large surprises from previous electron parity violation experiments in the size of such effects, and by the absence of a separate presentation on these issues at the review from an accelerator physics point of view. As we all know in the Jlab parity violation experiments the accelerator is an intimate part of the experiment and apparatus.

We encourage MOLLER to consider recruiting additional help in this area and to publish what they may already know from previous experience and measurements in a refereed journal if not done already. We understand that MOLLER already has excellent members of the collaboration at Jlab who are experts in accelerator physics. It is our impression from certain comments at the review that the accelerator scientists at Jlab may be too overburdened with their main responsibilities to have the luxury to indulge in the types of academic studies of accelerator physics issues of particular relevance to MOLLER which could be publishable in refereed journals like Physical Review Accelerators and Beams. It is also well known that the pool of accelerator scientists at universities is shallow. On the other hand it strikes us that accelerator physics studies of the polarized beam phase space evolution in the Jlab accelerator provides a unique intellectual challenge for accelerator physics research which could be attractive for researchers in this area. These topics could be very suitable for a MS or PhD theses in accelerator physics, and as data is already in hand from previous parity violation experiments such research need not wait for actual MOLLER data.

We can suggest two possible mechanisms to attract more help in this area for MOLLER. There might be enough intellectual overlap between the Jlab polarized electron phase space evolution issues and the expertise recently developed by various groups working on the spin dynamics in accelerators for proposed searches for electric dipole moments in storage rings to find a willing and interested group to collaborate with, especially in view of the rather long time horizon of these proposed storage ring EDM experiments combined with the nearer-term PREX/CREX/MOLLER opportunities. Such work could provide nice PhD thesis topics in accelerator physics and also could help MOLLER to reduce the uncertainties in its extrapolations for certain systematic effects and better understand their sources. Another possible mechanism could be for someone in the present MOLLER collaboration to interest a MS or PhD student at their institutions to work under the joint direction of MOLLER university and Jlab scientists on such an accelerator physics project. One can take advantage of the programs like the DOE SCGSR fellowships to lower the barrier for conducting such work and also point out to potentially interested students the especially wide variety of job prospects for students who earn a MS or PhD in accelerator physics.

(2) **Beamline Vacuum Thin Windows**: Concepts for the thin windows were presented and it was recognized by the presenters that a more thorough analysis is needed to determine final thicknesses and shapes. A strategy for guarding against vacuum window failure will be needed.

(3) **Development of a FMEA** (Failure Modes Effects Analysis), while not formally presented during the review, was stated as being in process for the spectrometer magnets. This is a commendable practice towards understanding and assessing potential failure modes as well as discerning solutions to either mitigate, prevent, or reduce the impact of failures.

The committee received the charge on Oct. 21. The committee started to function on October 22. The review committee read all of the relevant materials then available and forwarded the following set of questions to the MOLLER collaboration on Nov. 13 with a request that the MOLLER collaboration address these questions at the review presentations:

Critical Design Questions

1. **Excess Statistical Noise/Helicity-pair asymmetry-width –** The combination of faster helicity-reversal, larger raster-size, and smaller scattering-angle (all taken to new extremes in MOLLER) may increase the MOLLER asymmetry width well beyond counting statistics. It can be plausibly and quantitatively argued (see Appendix A) that the large excess noise observed in the 0.5° Qweak luminosity monitors (lumis) arose from the random phase-slippage of the signal induced by the raster motion in the detector over the helicity-quartet width. This asymmetry width, which is directly proportional to the final statistical uncertainty, seems likely to be more than twice what the collaboration has assumed. How will this problem be addressed?
2. **Beam halo issue** - Measuring asymmetries near 1° with the MOLLER apparatus has some similarities to measuring asymmetries with lumi monitors in previous experiments. But to our knowledge, a lumi monitor at JLab has never been demonstrated to operate close to counting statistics while being free of seemingly random false asymmetries at the ppm level (the latter apparently being due to a mechanical asymmetry, a working hypothesis for which is helicity-dependent beam halos). We have read the document HCBA_for_MOLLER.pdf from an April 2019 review. What is the latest strategy for suppressing such false asymmetries in the MOLLER experiment? Is there new information from PReX lumis?
3. **BCM charge asymmetry systematics** – By the end of the Qweak run, different BCM's yielded different charge asymmetries with very high statistical significance, and thus yielded experimental asymmetries that differed by well over 2 ppb. It was a surprising but (barely) tolerable uncertainty in Qweak, but would be fatal to the MOLLER precision goals. Is there a strategy for understanding and minimizing such BCM systematics? Is there new information on BCM charge asymmetry systematics from the PReX experiment?
4. **BCM noise –** The collaboration proposes BCM noise levels of 10 ppm. Scaling the BCM resolution from the Qweak NIM article to MOLLER, assuming two BCMs measuring 2 KHz pairs, a resolution of

~ 60 ppm could be achieved in MOLLER. (Or 42 ppm by averaging four BCMs.) The Qweak BCMs with digital receivers required a decade of design iterations before finally being successfully fielded. Is there a strategy for achieving a factor of ~4 reduction in BCM noise (from the local oscillators?) on the time scale for the first MOLLER experiment run?

5. **Backgrounds –** The scheme to account for the 5 physics backgrounds in the target relies on comparing the measured (r,φ) distribution with simulation. Won't unanticipated sources of background, in the magnet structure, downstream beamline, and the thick exit window of the magnet vacuum box interfere with this scheme? As well as contribute additional background? How will asymmetries be assigned to these additional sources of background? How well have simulations already explored the potential impact (dilution & asymmetry) of these types of backgrounds, including from hyperon production in the target and elsewhere? Will φ-asymmetric backgrounds such as can arise from the corners of the square raster, or misalignments, be tractable in a 7-sector geometry which lacks basic left-right and up-down symmetry?
6. **Detector background** – What is the fraction of light-weighted soft background in the main detector? How will this be measured or estimated? Is the simulation realistic enough (including alignment tolerances of the collimators, coils, and realistic raster sizes, etc.) to take these estimates seriously?
7. **Magnet feasibility** – We would like to see drawings showing slices thru the beamline near the start of the first and second coils (ie, near z ~ 6m and ~10m in Figure 18 of the 2016 pCDR) , so that we can see that everything fits and that the azimuthal acceptance is not encroached. We also need to see a figure like Fig. 19 in the Qweak NIM paper (NIMA 781, 105 (2015)) that shows the choke points with rastered beam using a highly asymmetric aspect ratio. This would allow us to see what problems the collimators are/are not solving, and what problems might arise with the magnet coils & beam pipe with respect to some reasonable multiple of the multiple scattering angle, including magnet/collimator alignment tolerances and the raster size (with its corners) as it grows along z.
8. **Alignment –** Can the MOLLER magnet coils be aligned to the required specification? For the individual coils, are the mechanical tolerances of the formed coils smaller than the ultimate alignment tolerances, such that alignment is a well-posed problem? Given realistic misalignments of the coils, what is the impact of the stray field along the beamline on the beam downstream of the target (which contains a large flux of low energy electrons)? Does this significantly contribute to the background in the detectors, or to heating of the downstream beam-pipe?

These questions informed the committee's interactions on the agenda for the Jlab review meeting, reproduced below:

Thursday December 12
8:00 - 8:40: Closed committee session
8:40 - 9:15: Science/Experimental Technique: Kumar
9:15 - 9:40: MOLLER Experiment Overview, Requirements: Pitt
9:40 - 10:20: MOLLER Statistics and Systematics: Paschke
10:20 - 10:35: Break
10:35 - 11:05: Liquid Hydrogen Target: Covrig
11:05 - 12:15: Spectrometer: Mammei/Fair

12:15 - 1:30: Closed committee working lunch
1:30 - 2:20: Integrating Detectors: Gericke/McNulty
2:20 - 3:10: Tracking Detectors: Armstrong/Liyanage
3:10 - 3:30: Break
3:30 - 4:05: Infrastructure and Integration: Gomez
4:05 - 4:20: Shielding Simulation: Gal
4:20 - 5:45: Executive session
5:45: Homework Assignments

Friday December 13
8:00 - 8:30: DAQ/Online: King
8:30 - 9:00: Beam Diagnostics and Monitoring: Pitt
9:00 - 9:30: Polarized Beam: Paschke
9:30 - 9:55: Polarimetry: Gaskell
9:55 - 10:10: Break
10:10 - 10:40: Response to technical recommendations from previous reviews: Pitt
10:40 - 11:00: Key Performance Parameters: Fenker

11:00 - 11:45: Homework Report
11:45 - 1:00: Closed Committee Working Lunch
1:00 - 4:30: Executive Session
4:30 - 5:00: Close-out

MOLLER delivered the CDR on the Friday November 22 deadline.

After the first day of review presentations on Thursday Dec. 12 the review committee issued the following homework questions to the MOLLER collaboration:

Homework Questions:

1. Please look at the calculation of spin dependence of Cerenkov radiation posted to the arXiv by I. B. Khriplovich (arXiv 0808.1500). Under the assumption that the formula presented in this paper is correct and given its different energy dependence on the longitudinal and transverse components of the incident electron spin, please make a rough estimate of or upper bound on the size of the systematic error in the quartz detector.
2. For the excess noise due to the raster in the main detector, please provide a cross-section weighted prediction of the rate variation due to the raster angle of +/- 150 microradians in the detector.
3. Jlab routinely de-rates the accelerating cavity gradient to reduce rf trips. If we reduce the energy gain of the north linac by 10 MeV and increase the energy gain of the south linac to compensate, how much transverse polarization does this produce at the target? (to estimate how much we will be changing the settings of the horizontal Wien filter).
4. Please provide a clear summary of what single-sector sensitivities have been simulated (referring to the CDR).

5. For the tables 2 and 3 in the CDR which list the different sources of statistical and systematic error, please provide, where it exists, what has been achieved for the relevant parameter in previous experiments (Qweak, PREX,…).
6. Please provide a sketch of the large downstream (~2 meter?) diameter window closest to the main detectors.

The responses of the MOLLER collaboration to these questions were presented, discussed, and uploaded to the Indico site along with the rest of the presentations on Dec. 13, 2019. The committee worked on the report and sent a draft to Howard Fenker on January 3, 2020. The chair forwarded to the committee fact-checking comments from the MOLLER collaboration relayed by Thia Keppel. The committee submitted its final report on January 10, 2020.