October 24, 2017

Final Report
Muon (g-2) Operational Readiness Review

1. Introduction

The Fermilab Program Planning Office (Steve Geer, Pushpa Bhat) charged a committee to review the operational readiness of the Muon (g-2) experiment in the fall of 2017. The charge is provided in Appendix A and the committee membership is provided in Appendix B. The review took place on 02-03 October, 2017 and the agenda and the relevant materials are available from this URL, https://indico.fnal.gov/conferenceDisplay.py?confId=15388. Following the last talk, the committee met to discuss first impressions, to formulate additional questions, and to make writing assignments. In the days following the review some additional material was provided in response to requests and questions from the committee.

This report describes the findings and recommendations of the committee based on the talks presented at the review, on the answers to the questions asked during the review, and on discussions among the committee members. Prior to the issuance of this Final Report, a draft version was shared with the spokespersons of the experiment in order to provide them with an opportunity to correct any factual errors. The replies and recommendations enumerated represent the consensus opinion of the committee as a whole.

Each section below addresses one of the principal charge questions. The names of the committee members whose primary responsibility it was to address this particular charge question are included in parentheses at the beginning of each section. The lead writer has her/his name starred (*). Each section includes "Findings", "Comments", and "Recommendations".

2. Charge question #1

(A. Aparicio, B. Flaugher*, J. Blazey)

Is there a completed Experiment Operations Plan (EOP) document? The document should include (a) an outline of the Science goals (b) a description of operations tasks and how they will be covered, (c) ES&H activities and how they will be managed, (d) organization charts showing the management structure for the experiment and how it interfaces with the laboratory, (e) Fermilab resources and roles as they pertain to each Division (f) the model for data processing and analysis including the computing budget and effort required, (g) a list of the identified

resources available, and (h) a description of the roles and responsibilities of each institution together with a list of support required by each institution from funding agencies.

Not quite – there is a solid draft that includes items a-h, but a few things are missing as discussed in the recommendations.

2.1 Findings

- A draft Experimental Operations Plan (EOP) for the Muon (g-2) experiment has been written describing the main operational tasks.

- The EOP also describes the roles and responsibilities of the Fermilab Divisions, including ESH&Q.

- The EOP provides an estimated budget required to operate the experiment from FY2018-2020.

2.2 Comments

- While the EOP describes the roles, resources and commitments of each institution, there is no formal documentation such as SOWs or MOUs that confirm that the institutions are willing and able to fulfill these roles. Such documentation would likely be useful to ensure there are no misunderstandings that would result in major operational risks.

- The ESH&Q activities described neither address radiation safety requirements (e.g. controlled access needs), nor Operational Readiness Clearance processes, which are important parts of the overall ESHQ oversight.

- It appears that the budget assumes that university research grants will provide support for their associated commitments to g-2 operations, including travel to Fermilab (e.g. there is no G&V component).

- An analysis coordinator has not been appointed, which may be hampering progress associated with analysis preparations.

- The responsibilities of the shift personnel are not described in detail nor the lines of authority for those on shift. This could lead to confusing situations in the control room that may cause undue operational risk.

- The information provided does not allow a quantitative comparison of whether sufficient personnel effort is available to commission, take data, and publish first results. There are two impediments to making this evaluation. First, the FTEs available were tallied based on the ill-defined metric of "fraction of research time", so that each person is normalized to a different total number of effort hours. Second, an estimate of the FTE required for commissioning, data taking, and publication was not provided.

2.3 Recommendations

1. Determine the number of FTEs needed to commission and operate the experiment and to produce first physics results. Tally the available FTE in a consistent manner to facilitate an assessment of whether sufficient effort is available. Modify the EOP to include this information.
2. Include reference to Radiation Safety and Operational Readiness Clearance processes in the EOP.
3. Finalize the EOP and obtain the required sign-offs.
4. Formalize an agreement with each institution providing operations support to help ensure expectations of all parties are clearly defined.
5. Prior to the start of physics-quality data taking, develop lines of authority and responsibilities for shift personnel, including a shift captain, and document them.
6. Appoint an analysis coordinator as soon as possible and no later than the end of the calendar year.
7. Work with the laboratory and collaboration to identify additional effort needed to meet your commissioning and physics goals, particularly for systems critical to success.

3. Charge question # 2

(D. Denisov, R. Tesarek*)

Has it been demonstrated that the experiment is ready for physics-quality data taking? If not, what actions are required to make it ready? Is there a clear plan for monitoring (the beam and) the data quality and has the associated infrastructure been tested? If not, what actions are required to adequately monitor the data quality?

The experiment acknowledges that it has not yet been demonstrated that the apparatus is ready for physics-quality data taking. Several detector subsystems need to be (re)commissioned in their final configurations and the proton and muon beam lines both need to be tuned-up to deliver design intensity. Considerable work remains prior to achieving physics-quality data, but the necessary work is largely known.

Yes, the associated infrastructure for monitoring beam and data quality has been

demonstrated, although performance metrics may have to be further optimized.

3.1 Findings

- A five week "Engineering Run" occurred in 2017 and utilized a reduced-rate muon beam without proton removal.

- All detector systems were examined during the 2017 Engineering Run. Performance issues were identified with several systems and must be addressed before physics-quality data taking can begin.

- Mitigation strategies to address the performance issues identified in the Engineering Run have been developed and are being implemented during the 2017 Shutdown.

- Once the mitigation strategies are in place, the collaboration is planning additional beamline and detector commissioning before physics-quality data taking.

- A Commissioning Run is currently scheduled for Nov-2017 through Feb-2018, after which, physics-quality data taking is scheduled to begin.

- Five systems have zero spares and the WFD5 5 channel digitizer system has eight spares for 312 units (2.6%). For some systems, components may be repaired instead of replaced.

3.2 Comments

- Low-rate beam commissioning was extremely useful, but understanding the performance and reliability of the pulsed power systems at high-rate is essential for efficient experiment operation.

- There does not appear to be sufficient expertise available to address the issues associated with the pulsed power systems in a timely manner. This poses a significant risk to the commissioning time scale and, by extension, the physics goals.

- The storage ring vacuum appears to limit the ability to run the electrostatic kickers and quadrupoles and has a major impact on the stored muon beam quality. While improvements have been made and plans formed to increase pumping capacity, outgassing from the trackers appear to be the most significant remaining limitation on vacuum quality. Testing and mitigation strategies to resolve the outgassing from the tracker should be implemented at the earliest practical time.

- A commissioning plan was outlined that provides first physics quality data in Feb 2018. It may not be possible to complete all commissioning tasks/studies on this timescale.

- In achieving a timely publication of first data, it would be useful to have a detailed commissioning and analysis plan that includes prioritization of critical tasks.

- For high risks systems, it would be prudent to ensure adequate spares have been identified or an acceptable repair plan has been developed and documented.

3.3 Recommendations

8. Include in your commissioning plan a list of priorities and minimal performance thresholds for critical systems to conform with first publication goals.

4. Charge question #3

(J. Cherwinka, P. Derwent*, R. Plunkett)

Is there a well-understood run plan for FY17, consistent with accelerator schedule and performance?

Yes, there is a well understood run plan for FY2018.

Have adequate resources from the laboratory and the collaboration been identified for an efficient and safe running of the experiment and for maintenance of the detector, and is it clear who is responsible for what?

No, there appear to be resource shortfalls in areas critical to their success. While collaborators appear to understand their responsibilities, there are no formal documents to establish responsibility for labor or M&S contributions.

4.1 Findings

- The accelerator run plan ramps to full intensity by February 2018.

- Full intensity corresponds to 1e12 POT in 16 pulses, separated in two batches of eight (with 10 msec time between pulses).

- There are multiple pulsed power supply systems that must pulse in burst mode at 100 Hz and average 11.43 Hz.

In the Accelerator : Li Lens, PMAG, DR Inj Septa, DR Abort Septa
In the Ring: Injection Kickers, Quadrupoles

- The spares budget presented in the EOP was $100k in FY18 and $10k in FY19 and FY20.

- The speakers identified multiple systems that require modifications to mitigate issues identified during the 2017 Engineering Run. Many of these modifications are scheduled to finish just-in-time for FY2018 Commissioning Run.

- The necessary vacuum has not been attained. The cause is believed to be outgassing from the tracking detectors.

- There is sparking in both the quadruples and kicker magnets. This is exacerbated by the vacuum situation, but may be a problem on its own that could limit the physics sensitivity of the experiment.

4.2 Comments

- Fermilab PPD is identified as being responsible in the EOP for the kicker and quadrupole systems. The Rings Ops manager identified these as areas where the support team is light. As PPD does not have enough experienced pulsed power supply engineers, the experiment will depend on experts from BNL and Cornell (where the systems originated). Given the importance of these systems to the success of the experiment, this may pose a significant risk to the success of the experiment.

- The run plan calls for the completion of a significant amount of work by February and it is not clear that all the resources exist. Commissioning and optimizing all the upgrades and modifications will take significant effort.

- The rings spares components seems thin, especially given the expected minimal spares budgets.

- The commissioning schedule appears optimistic given the number of items that must work better than the previous run.

- It would be useful to clearly define the minimum requirements for each of the subsystems before the experiment can take its first physics-quality data.

- Resources appear to be tight, especially on pulsed power supply support and, perhaps, the M&S for critical spares.

4.3 Recommendations

9. Generate a resource loaded spreadsheet (or equivalent) for commissioning, and use it in operations planning. This should include work for all subsystems (vacuum, detectors, field probes, DAQ, etc.).
10. Work with the laboratory and collaboration to identify the resources needed to address shortfalls in areas critical to success.

5. Charge question #4

(M. Kirby*, M. Neubauer)

Are there robust plans for data processing and data analysis? Have adequate resources from the laboratory and collaboration been identified for data analysis to meet these goals?

Not yet – their plans for data processing and data analysis are under development. Based on current assumptions, there appear to be adequate resources.

5.1 Findings

- The Muon g-2 experiment presented a plan for the processing of the initial physics data period based upon their experience from the Summer 2017 Commissioning run experience. The estimated resources requested for this initial dataset is approximately 18 M CPU hours for data reconstruction and 9 M CPU hours for simulation. The corresponding storage request for the raw MIDAS data, reconstructed data, and simulation samples is approximately 2 PB of Enstore tape. These estimates align with the requests that were made at the February 2017 SCPMT presentation.

- The experiment presented the current development of the offline reconstruction to include the calorimetric reconstruction of omega_a, tracking reconstruction for muon beam profiling, and plans for the development of the omega_p calculation. The plan covers most aspects of the analysis path necessary for completion of the initial experimental results. The experiment highlighted several aspects of the offline reconstruction where assistance from SCD expertise might help identify opportunities for significant performance improvements.

- A detailed organization chart for the g-2 Production Group was presented that included utilizing both local and remote effort to manage and operate the offline production workflows and software development. The current status of the production workflows was presented highlighting the extensive utilization of SCD/FIFE services within those workflows. The need for additional SCD/FIFE expertise was highlighted by the experiment in order to streamline workflow, provide access to additional computing resources outside of Fermilab, and to incorporate additional services such as POMS.

5.2 Comments

- The Muon g-2 experiment has made significant progress incorporating the recommendations of the 2017 Computing Review. The successful processing of the summer 2017 commissioning dataset provides a baseline for understanding the accuracy of the computing model for the experiment. The presentation of the

expected resource needs for the coming initial physics dataset did not appear to differ significantly from the estimates of February 2017. It's important for the experiment to present the assumptions used in those estimates and compare them with the results of the commissioning dataset performance.

- The recognition of specific areas where SCD expertise could make significant impact on the reconstruction software is an important step to decreasing computing resources needs. Having a focused effort will be important to address large memory footprints in offline software and to take advantage of the significant progress made in multithreading algorithms. To our knowledge, the experiment has not formally requested SCD's assistance.

- The creation of a focused and operational Production Group as soon as possible is an important part of achieving the physics publication goals of the experiment. The formation of the Production Group has occurred, but the recent formation combined with turnover in personnel, makes it important that they continue to focus the development of full end-to-end production and analysis code. The experiment acknowledged the need for SCD/FIFE assistance in improving workflows, but they did not estimate the needed effort level that would be requested from SCD (nb. these estimates have since been provided).

- The analysis to determine omega_p appears to have expertise concentrated among very few people.

5.3 Recommendations

11. Update and refine the estimates for the computing resource needs by utilizing the measured performance of a (near) final and complete version of the reconstruction and calibration software. Corrections for large memory footprint should be called out, if any. Include the resources necessary for the omega_p determination.
12. Generate a more thorough assessment of the simulation samples needed to achieve your physics goals, including first publication.
13. Formally engage SCD in a discussion to identify the relevant expertise effort needed to improve performance of the reconstruction software and the associated data handling and work flow.
14. Further investigate how best to leverage existing software and computing tools from outside the experiment (e.g. OSG, AWS) for both simulation and production workflows.

6. Charge question #5

(J. Blazey, D. Denisov*)

Are there clear goals set for reporting and publishing the results from the experiment in a timely fashion?

Yes, there are clear goals set for the publication of Muon (g-2) results with uncertainties of 400, 200, and 140 ppb in 2019, 2020, and 2021, respectively.

6.1 Findings

- A series of NIM articles for the major subsystems are planned as well as two PRD style papers on field shimming and analysis and muon beam dynamics.

- Publications of g-2 measurements with uncertainties of 400, 200, 140 ppb are planned in CY19, 20, and 21, respectively.

- The experiment has internal committees to coordinate reporting the results at meetings and conferences and publishing results in journals.

6.2 Comments

- The major components of the analysis chain are well understood. However, the full analysis chain has not yet been exercised and the coordination between analysis sub-groups is in the initial stages of development.

- The analysis organization includes operational, software, algorithm, and physics tasks. It is not clear if this organization is optimized toward reaching physics goals of the experiment.

- The collaboration should consider publishing an overview NIM paper describing the experiment that precedes NIM articles on specific subsystems. This paper could be used as the main detector reference for Muon (g-2) publications.

- The proposed publication schedule appears aggressive and will require quick commissioning of the experiment, reaching multiple operational specifications, well understood algorithms, and extensive analysis and computing efforts.

6.3 Recommendations

15. Develop a schedule with well-defined milestones and decision points for the first publication.

7. Charge question #6

(D. Glenzinski*, all)

Does the committee recommend further actions to ensure full exploitation of the Muon (g-2) program?

Nothing beyond what was included in the previous recommendations.

7.3 Recommendations

None.

8. Summary

The Muon (g-2) experiment was reviewed for its data-taking and analysis operations readiness. The review committee was provided with a set of Muon (g-2) documents relevant to addressing the charge questions. The Muon (g-2) collaboration also made a full day's worth of presentations to the review committee. The committee was grateful for all the collaboration's effort to provide the required input.

The committee wishes first to congratulate Muon (g-2) on the successful start-up during the 2017 Engineering Run. The committee was impressed with the level of enthusiasm and expertise evident in the presentations and discussions during the review. The committee applauds Muon (g-2)'s ability to produce, so quickly once beam was delivered, the first "wiggle plot".

While there are areas of concern, the committee identified no show stoppers. And although a significant amount of work remains prior recording the first physics-quality data, the Muon (g-2) collaboration is motivated and possesses a deep understanding of what's required to achieve their physics goals. The committee has provided above a list of 15 recommendations that are meant to mitigate the most significant risks to achieving the first physics goals. The committee suggests that the Muon (g-2) collaboration provide regular progress reports at the Experiment Management Group meetings.

Appendix A – Charge

Muon g-2 Experiment Operational Readiness Review

October 2-3, 2017

CHARGE

The Muon g-2 experiment completed the installation of its detectors and began commissioning with muon beam a few weeks before the summer shutdown of the accelerator complex this year. The commissioning of the experiment will be completed once the beam returns in November and physics data-taking operations will begin. The primary goal of the experiment is to measure the muon's anomalous magnetic moment with a precision of 0.14 parts per million, a four-fold improvement compared to the BNL E821 result, to shed light on the >3 sigma deviation from the Standard Model, seen in the BNL experiment.

We would like the committee to review the preparations of the experiment for running, plans for maintenance & operations of the detectors, and data taking and analysis, including the current status of the detector, the status of the online and offline software, and the run plan.

In particular:

1. Is there a completed Experiment Operations Plan (EOP) document? The document should include (a) an outline of the Science goals (b) a description of operations tasks and how they will be covered, (c) ES&H activities and how they will be managed, (d) organization charts showing the management structure for the experiment and how it interfaces with the laboratory, (e) Fermilab resources and roles as they pertain to each Division (f) the model for data processing and analysis including the computing budget and effort required, (g) a list of the identified resources available, and (h) a description of the roles and responsibilities of each institution together with a list of support required by each institution from funding agencies.

2. Has it been demonstrated that the experiment is ready for physics-quality data taking? If not, what actions are required to make it ready? Is there a clear plan for monitoring (the beam and) the data quality and has the associated infrastructure been tested? If not, what actions are required to adequately monitor the data quality?

3. Is there a well-understood run plan for FY18, consistent with accelerator schedule and performance? Have adequate resources from the laboratory and the collaboration been identified for an efficient and safe running of the experiment and for maintenance of the detector, and is it clear who is responsible for what?

4. Are there robust plans for data processing and data analysis? Have adequate resources from the laboratory and the collaboration been identified for data analysis to meet these goals?

5. Are there clear goals set for reporting and publishing the results from the experiment in a timely fashion?

6. Does the committee recommend further actions to ensure full exploitation of the muon g-2 experimental program?

We request a brief written closeout report from the committee addressing these questions by October 31, 2017.

Appendix B – Committee Membership

Angela Aparicio (Fermilab)
Jerry Blazey (Northern Illinois University)
Jeff Cherwinka (University of Wisconsin, Madison)
Dmitri Denisov (Fermilab)
Paul Derwent (Fermilab)
Brenna Flaugher (Fermilab)
Doug Glenzinski (Fermilab – Chair)
Mike Kirby (Fermilab)
Mark Neubauer (University of Illinois, Urbana-Champaign)
Rob Plunkett (Fermilab)
Rick Tesarek (Fermilab)