Office of Project Assessment
Status Review Report on the

Muon g–2 Project
at Fermi National Accelerator Laboratory

April 2016
A Department of Energy/Office of Science (DOE/SC) review of the Muon g–2 project’s status, was conducted on April 6-7, 2016. The review was conducted by the Office of Project Assessment (OPA), and chaired by Kurt Fisher, OPA, at the request of Michael Procario, Director, Facilities Division for High Energy Physics. The purpose of the review was to evaluate the Muon g–2 project’s status, as the project had received Critical Decision (CD) 2/3, Approve Performance Baseline and Approve Start of Construction in August 2015; and focused on aspects of the project—technical, ES&H, overall cost, schedule, and management.

The Committee determined that the Muon g–2 project team made significant progress since the June 2015 review. The Committee saw no issue with the project completing CD-4, Approve Project Completion as planned; however, the early completion date is aggressive and will require a Transition to Operations Plan with schedule to allow priorities to be identified and planned appropriately. Finally, the Committee supported proceeding with “Stage 1” of the new-design inflector prototype and then getting DOE guidance regarding implementation for any potential “Stage 2” inflector enhancements, when appropriate.

**Accelerator**

The Committee judged there was no concern related to the work scope being completed by the CD-4 date of third quarter FY 2019; however, there is concern that the early completion date of March 2017 is at risk. The project team is encouraged to socialize a “start of storage ring commissioning” date, and optimize schedules of g–2 project deliverables and Accelerator Improvement Projects (AIP) to meet this date.

The Committee suggested that Fermilab should pursue developing a detailed Transition to Operations Plan, including a schedule, to set these priorities. This plan should be developed in a way that additionally defines the prioritization between installation and commissioning activities following the FY 2016 summer shutdown.

**Storage Ring / Technical Integration**

The project team presented a new-design/improved inflector to enable additional physics capability, with a 60% higher transmission as an alternative future option. It incorporates modified (open) ends that also reduce field at the shield location and newly available enhanced shield material. The next step for this option is to fabricate and test a Stage 1 prototype inflector cold mass (in-project cost $400K including 40% contingency over one year); this is beyond the Key Performance Parameter (KPP).

The Committee judged that the schedule push for a 2017 start of muon measurements should not be allowed to compromise field quality, resulting in deterioration of data quality and usefulness.

The Committee recommended that a plan be developed for commissioning and Transition to Operations should be implemented and completely agreed to by all parts of the Laboratory. In particular, the project should work with laboratory operations management to initiate planning
for an Accelerator Readiness Review (ARR), so that the project can make sure all of the requisite
documentation and safety systems are in place.

The project requires significant technical resources to maintain the installation schedule over the
next year; coordination with, and commitment of the resources by Accelerator, Particle Physics,
and the Technical Division is critical moving forward, in particular after the summer 2016
accelerator shutdown is complete.

**Detector**

The Committee identified a concern that the straw tubes necessary for the tracker are not already
available. However, management is well aware of this and is actively working with the straw
tube provider to help them successfully manufacture the straws. Management is aware that they
may have to seek an alternative source for the straws shortly. Fermilab procurement should be
actively engaged in this effort.

While the prototyping indicates a very well designed experiment, there is still an enormous
amount of work to be done in actually assembling the calorimeter, tracker, data acquisition
(DAQ) system, etc. and then turning these individual elements into an experiment capable of
making an extremely precise measurement of g–2.

**Cost and Schedule**

The Committee noted that the project has performed well since the June 2015 DOE/SC review.
Since May 2015, $9 million of work has been completed, and $12 million of work remains.
During this period, $1.3 million in contingency was used. The Cost and Schedule Performance
Indices are 1.0 and 0.99 respectively.

The project appears to have sufficient contingency to add the proposed Stage 1 inflector scope
enhancement. This scope enhancement does not create additional schedule or cost risk to the
current baselined scope.

**Project Management**

The Committee judged that the ES&H aspects of the project are being properly addressed. At
this time, the project team has yet to fully implement an ARR program. The ARR committee has
yet to be chartered, and the project needs to move forward with creation of the ARR committee
and subsequent implementation of reviews.

The Committee reiterated that vigilance related to completing the remaining procurements on
schedule and managing vendor delivery/performance is critical to the early delivery of g–2.

The shared technician and magnet fabrication resources could be a challenge to complete g–2 to
support early science. Vigilance related to early planning, communicating, and assigning
Fermilab labor resources will be key to the experiments ability to collect early data.
Transition to operations and commissioning planning efforts are in the early stages and should be a high priority moving forward.

**Key Recommendations**

- The g–2 project, in consultation with the program office, should further evaluate the new inflector strategy.

- Develop a detailed, integrated Transition to Operations Plan and schedule that includes all activities from commissioning through experiment start-up (including accelerator readiness). Present the plan and schedule to the program office no later than June 30, 2016.
CONTENTS

Executive Summary .......................................................................................................................... i
1. Introduction ............................................................................................................................. 1
2. Technical Systems Evaluations .............................................................................................. 2
   2.1 Accelerator ..................................................................................................................... 2
   2.2 Storage Ring .................................................................................................................... 4
   2.3 Technical Integration ..................................................................................................... 7
   2.4 Detectors ......................................................................................................................... 7
3. Environment, Safety and Health ......................................................................................... 10
4. Cost and Schedule ............................................................................................................... 12
5. Project Management ............................................................................................................ 15

Appendices
A. Charge Memorandum
B. Review Participants
C. Review Agenda
D. Cost Table
E. Funding Table
F. Schedule Chart
G. Management Chart
One of the more persistent hints of new physics has been the deviation between the measured muon anomalous magnetic moment, \((g-\frac{2}{2})\), and its Standard Model expectation, where both are currently determined to a precision of 0.5 parts per million. This fundamental measurement has been pursued for decades with increasing precision. The discrepancy of several standard deviations that, if true, could be caused by the quantum effects of virtual particles too massive to be produced and detected directly has been interpreted to point toward several attractive candidates for Standard Model extensions such as supersymmetry, extra dimensions, or a dark matter candidate. Because a precision measurement of \(g-2\) is sensitive to virtual particles, it offers a strategic opportunity to probe areas of TeV-scale physics beyond the reach of the Large Hadron Collider (LHC). Should the LHC discover new physics that would confirm the \(g-2\) discrepancy, then precise determination of \(g-2\) is expected to provide direct measurements of the coupling constants of the new particles responsible for the discrepancy, fundamental parameters of the underlying theory, and a window on the underlying symmetries of the new physics. For many possible cases, it is expected that these parameters will not be measured with adequate precision at the LHC alone.

The experimental technique involves measuring the precession frequency of the muon spin vector in a well-understood magnetic field; in this case the spin vector will be reconstructed from the angular distribution of muon-decay electrons in a storage ring and the precession of the spin vector in the storage ring’s magnetic field will be tracked over time. The prior \(g-2\) experiment at Brookhaven National Laboratory (BNL Experiment E821) ended with a successful, statistics-limited measurement of \(g-2\) and is one of the most heavily cited High Energy Physics (HEP) experiments, with more than 2,000 citations.

The present Muon g-2 project at Fermilab is fabricating a new experiment that seeks to improve the measurement of the muon anomalous magnet moment. The project repurposed the storage ring from the prior BNL experiment and is providing new injection and detector systems in order to utilize the high intensity proton beam at Fermilab to produce the needed secondary beam of muons. Transfer of the BNL storage ring to Fermilab occurred in FY 2013. In 2014, the P5 subpanel of the High Energy Physics Advisory Panel recommended completing the Muon g-2 experiment as an immediate target of opportunity for searching new physics and identifying future directions for the field.

New instrumentation for the storage ring is being provided, in part, by in-kind contributions from non-DOE sources including NSF. By virtue of having run the original apparatus for five years, the required technology and physics principles have been tested and demonstrated. Additionally, much of the expertise involved with the initial construction of the experiment is still available and remains involved, along with a number of new collaborators for the new Muon g-2 experiment at FNAL (FNAL Experiment E-989).

The present review is the first assessment of progress by DOE since the project was baselined (CD-2) and fabrication was approved (CD-3) in August 2015.
2. TECHNICAL SYSTEMS EVALUATIONS

2.1 Accelerator

The Committee was pleased to see the g–2 project well into the construction phase. Muon Campus Accelerator Improvement Projects (AIPs) and General Plant Projects (GPPs), needed by the g–2 project, are making progress and continue to show that resource allocation is balanced across the multitude of concurrent projects. There are still concerns regarding the spreading of resources going forward, but the project team is dealing with this (see Comments below). A total of $6.7 million of work remains to be done on accelerator systems. This is the largest remaining work of the Level 2 systems. Of the $6.7 million of work to be done, the majority is in the beamlines ($5.2 million).

2.1.1 Findings

Commissioning with beam to the target station dump is scheduled after the summer shutdown, October 2016.

Installation and check-out are scheduled to be completed by March 2017. Commissioning of beam into the storage ring is scheduled to follow installation, with some data obtained before the 2017 summer shutdown. This early completion date is challenging, and the review presentations made this clear. This date drives a number of our comments.

An internal review of the Delivery Ring AIP was conducted in February 2016; the Committee was presented with the review report.

The completion of the Delivery Ring AIP, the Recycler RF (radio frequency) AIP, and Beam Transport AIP are on the critical path for the start of beam commissioning.

At the June 2015 DOE/SC review, Fermilab was considering several approaches to deal with a booster batch timeline that satisfied all users. Since that review, Fermilab agreed on a default scheme with an added Booster cycle to the timeline (21 Booster ticks in a 1.4s NOvA cycle vs 20/1.33s), which provides 95% of what g–2 and NOvA each considers its nominal rate.

**Target and Beamlines**

Installation of the beamlines M1 to the target and M2 from the target to M3 is complete and ready for beam commissioning. Installation of the beamline M3 is ahead of schedule.

Installation of the beamline D30 straight section and beamlines M4, M5 are on the critical path.

This WBS element has the largest Estimate to Complete (ETC) in the project. The reason for this is twofold: 1) there are several large dollar value procurements that are expected to be delivered in the next few months—these are primarily power supplies and magnets; 2) the other area is installation effort expense.
At the June 2015 review, the Committee encouraged the project to test the kickers in the 100 Hz mode. None of the g–2 project kickers have been tested since the June 2015 review.

**Controls and Instrumentation**

MC-1 safety system interlocks are behind schedule due to coordination with Storage Ring work in MC-1 building, but these interlocks are not needed for ring shimming.

Proportional Wire Chambers (PWC) and ion chambers are retractable, using recycled bayonet cans. The needed bayonet can and anti-vacuum chamber modifications are behind schedule and over budget due to prototyping. Fermilab now has a solution they believe will work, and no further overruns are anticipated.

**2.1.2 Comments**

The Committee was concerned that remaining installation may still pose a bottleneck problem. A dedicated installation team should be in place after the summer shutdown.

The Committee commended the project for the recent Delivery Ring AIP review. This review identified a number of issues related to scheduling that could impact, not only the ability to commission the storage ring by June 2017, but also impact the delivery of g–2 scope by March. The Committee echoed these recommendations and encouraged the project to address them.

The risk analysis is up-to-date and comprehensive. The risks are related to either scheduled or cost (not technical), and are appropriately accounted for in contingency.

There are seven registered risks that are being closely tracked; the probability and cost and schedule impact of the majority of the risks is low.

While the Committee had no concern related to this work scope being completed by the CD-4 date of third quarter FY 2019, the Committee was concerned that the early completion date of March 2017 is challenging. The Committee encouraged the project to socialize a “start of storage ring commissioning” date and optimize schedules of g–2 project deliverables and AIPs to meet this date.

To this end, the Committee encouraged the laboratory to immediately develop a detailed Transition to Operations Plan, including a schedule, to set these priorities. This plan should be developed in a way that additionally defines the prioritization between installation and commissioning activities following the FY 2016 summer shutdown.

**Target and Beamlines**

The Committee’s recommendation at the June 2015 review was to test g–2 pulsed power supplies, particularly the kicker, in 100 Hz mode in order to gain some schedule contingency. No testing on g–2 project kickers was done. However, an AIP-funded kicker, similar to the g–2 kicker was recently tested in 100 Hz burst mode. The Committee commended the pulsed power
The group for this accomplishment, which partially addresses the Committee’s recommendation from the June 2015 review, and reduces the risk associated with these systems.

The Committee was pleased to see that an additional engineer, hired to work on the pulsed magnet power supplies, is providing significant contribution to the critical area of the project.

The M4 and M5 magnet installation is on the critical path, so receiving magnets late would jeopardize the early completion date of March 2017. Every effort should be made to ensure that the Technical Division produces these magnets on schedule.

**Controls and Instrumentation**

Electron-beam welding for the first anti-vacuum chamber was successfully completed without issues, using a titanium flange. An ion chamber is installed inside of the first ebeam-welded anti-vacuum box, which was installed inside a bayonet can. The unit passed a two-stage vacuum certification and is ready to install in the M2 line. As this work is now behind schedule, it should be closely monitored.

2.1.3 Recommendation

1. Immediately proceed with the formation of a team to develop a detailed Transition to Operations Schedule and Commissioning Plan. The initial components of this plan are needed by the end of the 2016 summer shutdown.

2.2 Storage Ring

2.2.1 Findings

The main storage ring magnet reached full current September 21, 2015, after repair of a high resistance indium joint. The 1.45T Key Performance Parameter (KPP) has been attained, WBS 3.2 has been closed out ($4.55 million), and turned over to operations. The Storage Ring (SR) Controls and Instrumentation, WBS 3.7 has also been closed out ($0.92 million). Automated handling of vacuum, cryogenics, and power supplies is fully enabled. Remaining SR work includes that in WBS 3.3 inflectors, WBS 3.4 vacuum, WBS 3.5 kickers, WBS 3.6 quads, and WBS 3.8 field.

Most significantly, the collective SR schedule has slipped two months; slippage is primarily due to difficulty in achieving required field uniformity, which is now essentially on a critical path. The “rough shimming” must be completed prior to vacuum installation. It is being “managed proactively”.

The main magnet shimming (WB S3.8, $1.38 million) involves trolley measurement, frequency measurement, passive shims, and active shims. It is noted that:

- The shimming plan comprises approximately 15 steps over approximately 9 months, per June 2015 review,
Shimming has been in progress for six months, since October 2015, after attaining full magnet current,
WBS 3.8 is presently estimated to be 43% complete as of end-February 2016,
Initial 1400ppm azimuthal variation around ring was reduced to 550ppm. Error sources are known; expectation is that 25ppm is attainable,
Attaining requisite field quality only using “easy knobs” is not possible, and finally,
Expanded shimming is underway—first, time-consuming shimming to re-shape/re-orient/re-position pole surfaces (83% complete), to be followed by fine-adjustment, “easy-knobs” to achieve the approximately 25ppm; anticipated completion is June 2016.

Inflector (WBS 3.3) enables efficient beam injection. The existing inflector’s lead can has been refurbished and a new state-of-the-art power supply was purchased. The new power supplies will be ready for installation in two weeks. The inflector (and first vacuum chamber section and peripherals) will be ready in November 2016.

A new-design/improved inflector to enable additional physics capability, with a 60% higher transmission is an alternative future option. It incorporates modified (open) ends that also reduce field at the shield location and newly available enhanced shield material. The next step for this option is to fabricate and test a “Stage 1” prototype inflector cold mass (in-project cost $400K including 40% contingency over one year); this is beyond the KPP. If successful, the prototype could become an early upgrade option. Alternatively, with DOE guidance/approval, out-of-project (or contingency) dollars could be used to fabricate a “Stage 2” completely new production inflector (cost $620K including 30% contingency over 1.5 years) of the new design for subsequent implementation in the SR.

Three kickers (WBS 3.5) move the injected beam into the main orbit. New kicker cages have been completed at Cornell, and full current pulsing at approximately <150ns has been demonstrated. Expected arrival at Fermilab is June 2016. The interface issue with the vacuum chamber via common element rails to be aligned with Fermilab’s rails (trolley continuation) is recognized/planned for.

Electrostatic quadrupoles (WBS3.6), per the CD-2 design, initially incorporated an outer Quad plate moved radially outward so as to avoid injected beam. However, it was not possible to achieve the increased 70kV needed at this larger radial position. A subsequent redesign with symmetric (equal-radially-positioned) plates (thus reducing muon count) but with new vertical standoff (recovering muon count) performed adequately per high voltage (HV) tests. HV pulsers have been ordered with an Experimental Test Accelerator (ETA), June 2016.

The vacuum chamber (WBS 3.4) is also on a critical path. Chamber cleaning (with ethanol) and trolley rail simplifications have been incorporated. Additional manpower has been deployed. A 10-7 torr without the need for vacuum ovens has been demonstrated.

The vacuum chamber (WBS 3.4) and quadrupole (WBS 3.6) have the largest SR ETCs. This is recognized by management. Additional manpower and resources have been dedicated to maintain schedule. The bulk of the manpower has no conflicts or outside project shutdown obligations.
2.2.2 Comments

Indeed it is advantageous, per plan, to not delay early muon measurement. Nonetheless, the schedule push for a 2017 start of muon measurements should not be allowed to compromise field quality, and thereby an ultimate deterioration of data quality and usefulness.

Any new design inflector installation can occur after initial 2017 measurement, when ready in a deployment of “Stage 1” or “Stage 2” new inflector design. Additionally, in any case, having a spare inflector for this single-point-of-failure inflector is attractive, as it reduces operational risk. A clear preferred implementation plan for the inflector Stage 1 and/or Stage 2 options is not completely defined.

The superconducting magnet system for the experiment has a demonstrated KPP 1.45T field strength and KPP 25ppm field quality over a single pole. Reducing azimuthal nonuniformity from 1400ppm down to 550ppm has been achieved, as has requisite 15um pole-to-pole alignment. Getting to the 25ppm KPP requires first, completion of shimming with “time-consuming-knobs”, followed by vacuum chamber insertion, then fine-tuning with “easy knobs”. It remains to demonstrate KPP 25ppm field quality around the full SR. If any unanticipated full-scale field correction implementation issues arise, impact to schedule would likely be large. Anticipated validation is June 2016; this will give timely indication of any potential schedule risk.

It is desirable to get quads/vacuum chamber deployed timely, so as to subsequently integrate and test performance with all components in place.

Several WBS components are at or near critical path. Resource competition with other Fermilab projects is recognized by management.

Overall, key remaining risks in the SR arena include: 1) finalization of the original inflector (cold test planned), 2) timely attaining global SR requisite field quality in the presence of all ring components, include quads and vacuum chamber, 3) timely access to labor, and 4) managing helium leak. With regard to the latter, repair is planned after magnet shimming and quad, kicker, and inflector tests are complete. The problem has been identified (in the lead can, likely in an isolator) and although repair cost is not high, it is a schedule risk due to necessary warm-up, repair, and cool-down time.

Indeed, with lessons learned applied, and by continuously updated planning and scheduling, the SR scope, schedule, and ETC are still credible. Furthermore, the SR risk analysis has been updated to reflect the real risks for completing the project and contingencies are acceptable. There are no significant risks that jeopardize CD-4 completion requiring management attention. The proposed “early finish” schedule is challenging, management is aware of the schedule risks (above), and manpower has been augmented in the critical areas.

2.2.3 Recommendation

2. The Committee supported proceeding forthwith with “Stage 1” of the new-design inflector prototype and getting DOE guidance re implementation paths for any potential “Stage 2” inflector implementation, as appropriate.
2.3 Technical Integration

2.3.1 Findings

The plan for the next year has many activities involving the accelerator beam lines, the storage magnet, and detectors. Many activities in the plan for the previous year have slipped so that several paths are all close to the critical path.

A detailed day-by-day Integration and Installation (I&I) plan has been made for the next three to four months.

The project will be integrating the Cornell kicker section in June, which will require interfacing with the vacuum chamber via common rails that need to be aligned.

The cryoplant refrigerator is shared with Mu2e, but built into the specification to have excess capability, with either functioning even if the other facility has an issue.

The Threshold KPPs for the Accelerator require beamlines M2, M3, M4, and M5 to be ready for installation, with the caveat “dependent on external factors”. Those external factors have been addressed and will not impact beamline installation relative to CD-4.

2.3.2 Comments

The Commissioning and Transition to Operations Plan should be implemented and completely agreed to by all parts of the Laboratory. In particular, the project should work with operations laboratory management to initiate planning for an Accelerator Readiness Review (ARR), so that the project can make sure all of the requisite documentation and safety systems are in place.

The project requires significant technical resources to maintain the installation schedule over the next year; coordination with, and commitment of the resources by Accelerator, Particle Physics, and the Technical Division is critical moving forward, in particular after the summer 2016 accelerator shutdown is complete. With so many activities and interfaces, the project needs to continue to coordinate, evaluate, and develop the detailed schedule.

2.3.3 Recommendations

None.

2.4 Detectors

2.4.1 Findings

The spokespersons and laboratory managers appear to have an excellent working relationship. The collaboration includes many talented individuals and seems enthusiastic about pursuing the experiment’s physics goals.
The prototyping of the calorimeter and tracker indicate that the detector performance will exceed that required to measure g–2 to the desired precision.

A subset of the data acquisition (DAQ) system is being exercised regularly and meets the requirements for the experiment.

All of the PbF2 crystals have been received by the experiment. Each crystal was subjected to a set of quality control (QC) measurements and as a result a small subset of crystals will be replaced by the manufacturer. The dimensions of each crystal were measured and will be used to optimize the assembly of the calorimeter.

All of the Silicon photomultipliers (SiPMs) necessary to readout the calorimeter are available. A laser calibration system for tracking gain stability had been incorporated into the calorimeter design.

Touch labor for installation procedures has been estimated based on calorimeter module stacking experience in the laboratory and at test beam sites. Final detector assembly will occur at Fermilab before installation. Space for the assembly at Fermilab has been identified in the D0 building.

The manifolds necessary for the tracker are being machined using facilities at Liverpool. With the exception of the tracker straws, all the other necessary parts (e.g. wire, feedthroughs, etc.) are available. QC procedures for the steps involved in assembling the tracker modules have been developed.

The vacuum chamber that holds the tracker modules has been modified and successfully passed the necessary QC checks. Based on this success the additional necessary vacuum chambers are being modified.

The uncosted labor (i.e., faculty, postdocs, graduate students) available to assemble, install, and operate the experiment is quite impressive and likely to be sufficient to the task.

2.4.2 Comments

As previously mentioned, there is concern that the straw tubes necessary for the tracker are not already available. However, management is well aware of this and actively working with the straw tube provider to help them successfully manufacture the straws. Management is aware that they may shortly have to seek an alternative source for the straws. Fermilab Procurement should be actively engaged in this effort. The Committee emphasized that it is important that management continues to aggressively pursue the procurement of the straws including exploring options that involve resources that might be available to members of the collaboration.

The schedule calls for the tracker manifolds to be machined over eight months. Given that the experiment is scheduled to be operational within about a year, management may want to exercise options sooner rather than later that would speed up the manifold production.

While the prototyping indicates a very well designed experiment, there is still an enormous amount of work to be done in actually assembling the calorimeter, tracker, DAQ system, etc.,
and then turning these individual elements into an experiment capable of making an extremely precise measurement of $g-2$.

2.4.3 Recommendations

None.
3. ENVIRONMENT, SAFETY and HEALTH

3.1 Findings

The Muon g–2 Risk Management Plan was issued on June 1, 2014, and delineates the process wherein a Risk Change Log is maintained to identify and track potential risks to the project. The project team effectively uses this tool to identify, track, and control risks to the project.

The ES&H aspects of the project are being properly addressed. The project responded appropriately to recommendations from previous DOE/SC reviews. ES&H programs are mature and implemented throughout all levels of the project, and are well-positioned to support project completion.

At this time, most activities conducted as part of the Muon g–2 project are performed by laboratory personnel and are addressed by the Fermilab ES&H programs. Integrated Safety Management (ISM) principles are employed in planning and execution of work throughout all levels of the project. The project prepared and implemented an ISM Program on July 3, 2014 (see the Integrated Safety Management (ISM) Program of the Muon g–2 Project v2.1, July 3, 2014), and this plan remains in effect. The respective plan delineates roles and responsibilities for ES&H, and mandates regular management walk-throughs of project installation sites.

Furthermore, the review also examined the project’s safety performance trends. From October 1, 2014, through March 31, 2016 (inclusive), the project recorded 82,275.16 hours worked. For that period, the Total Recordable Cases (TRC) rate was 0.00, and the days away from work, job transfers, or restrictions (commonly known as DART) rate was 0.00. In contrast, the Fermilab TRC and DART rates for FY 2015 were 0.96 and 0.64, respectively. For FY 2016 (through March 31, 2016), the rates were 1.36 and 0.52, respectively.

The project prepared a Preliminary Hazard Analysis Report, which was approved September 16, 2013. This document attempted to identify and predict all potential hazards during the project’s construction, installation, and operational phases. The project periodically updates the preliminary report. The most recent Hazard Analysis Report for the Muon g–2 project v2.6 was issued on August 12, 2015.

The project further developed and updated the Quality Assurance (QA) Program, which was issued on June 26, 2014, and received approval by the Project Manager on August 3, 2015.

The project met the requirements of the National Environmental Policy Act (NEPA). The NEPA Categorical Exclusion (10CFR1021, Subpart B, Appendix B1.30, B1.31, and B3.10) for g–2 was issued on December 20, 2012.

Project Controls has essentially completed installation of Personnel Protection System (PPS)—the radiation safety system and electrical safety system—in the M5 Line Tunnel.
3.2 Comments

The project has an excellent health and safety record, and diligence to ISM principles is noteworthy.

Based on discussions in several break-out sessions, the project does not currently have a developed programmatic plan or methodology in place that adequately supports transition from the current project phase to operations.

Although the Accelerator Safety (AS) Program is independent of the Muon g–2 project, consideration should be given to reporting on progress and implementation of the AS program with respect to the project in forthcoming DOE/SC reviews.

At this time, the project team has yet to charter and fully implement an ARR program. The project needs to move forward with creation of the ARR committee and subsequent implementation of reviews.

3.3 Recommendation

3. Provide a plan to the Program Office that describes the process for addressing requirements of the Accelerator Safety Order, specifically requirements for development of an Accelerator Safety Envelope (ASE), ARRs, and installation of PPSs. The plan should be provided within three months.
4. COST and SCHEDULE

4.1 Findings

<table>
<thead>
<tr>
<th>PROJECT STATUS as of February 29, 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Type</td>
</tr>
<tr>
<td>CD-1</td>
</tr>
<tr>
<td>CD-2</td>
</tr>
<tr>
<td>CD-3</td>
</tr>
<tr>
<td>CD-4</td>
</tr>
<tr>
<td>TPC Percent Complete</td>
</tr>
<tr>
<td>TPC Cost to Date</td>
</tr>
<tr>
<td>TPC Committed to Date</td>
</tr>
<tr>
<td>TPC</td>
</tr>
<tr>
<td>TEC</td>
</tr>
<tr>
<td>Contingency Cost (w/ Mgmt. Reserve)</td>
</tr>
<tr>
<td>Contingency Schedule on CD-4</td>
</tr>
<tr>
<td>CPI Cumulative</td>
</tr>
<tr>
<td>SPI Cumulative</td>
</tr>
</tbody>
</table>

The Total Project Cost (TPC) has remained constant at $46.4 million, and the CD-4 date has remained at third quarter FY 2019. The project is 70% complete as of February 2016 with $5.65 million of cost contingency (46% BAC to go) and 22 months of schedule contingency (138% to go). There is a projected cost estimate uncertainty of $3.55 million on remaining work and a risk cost impact of $1.6 million at a 90% confidence level. The proposed contingency level has decreased $1.3 million since the June 2015 DOE/SC review. The $5.65 million in contingency remaining represents the contingency after subtracting the management’s estimate at completion. The project updates ETC monthly in areas of known cost increases, and a bottom-up ETC was completed eight months ago. A full bottom-up ETC is planned in two months. The schedule is mostly unchanged, and the critical path goes through accelerator construction and the installation of the M4/M5 beamline. Several major procurements not on the critical path are delayed (straw procurement and pulsed power supply procurement).

The project is proposing a scope enhancement to build and test a full-scale technical inflector model using recycled parts (Stage 1). The cost for this is $400K with 40% contingency included. An engineering estimate was completed and the majority of the cost is labor. The labor needed for the new inflector would involve an entirely different team separate from the baseline inflector scope. The project is also proposing to build a new inflector from all new parts with a cost estimate of $620K including 30% contingency (Stage 2).
The project has utilized and Earned Value Management System (EVMS) for approximately 24 months. A March 2016 SC EVMS Surveillance Review stated that the “FRA EVMS still meets the requirements and intent of the ANSI/EIA-748 standard.” Since August 2015, the risk registry has had 23 updates (6 modified, 3 added, 11 retired, and 3 realized). Given the remaining risks, the project stated that the overall potential for schedule delay is projected to be as much as six months from the early completion date. Major risks remaining include repairing the He leak in the lead can, cooling and powering the inflector, and uncosted scientific labor.

The necessary GPP projects are substantially complete and the remaining AIP projects needed for the project are scheduled to be completed this summer, well before the March 2017 need-by date. These AIPs include the Beam Transport, Recycler RF, and Delivery Ring.

The Level 2 milestone, Prototype test of Q1 Quadrupole Complete, was completed two months late. There were no prior Cost and Schedule recommendations from the June 2015 review.

4.2 Comments

The project performed well since the June 2015 review. Since May 2015, $9 million of work has been completed and $12 million of work remains. During this period, $1.3 million in contingency was used. The Cost and Schedule Performance Indices (CPI/SPI) are 1.0 and 0.99, respectively. Since May 2015, the combined estimate uncertainty and 90% confidence level of risk remaining was reduced by $2.45 million from $7.6 million to $5.15 million. The $1.3 million in contingency used during this period is a positive trend. At the current rate, the $5.65 million in contingency available is adequate to complete the project (approximately $3 million used at the current rate). A full bottom-up ETC that the project plans to perform in two months is prudent in order to fully examine the remaining cost to complete the project.

When determining to add new scope, the project set the following guidelines: contingency of at least 40% of cost-to-go (approximately $5 million), and contingency adequate to cover 100% of estimate uncertainty and 90% CL risk ($5.15 million). These guidelines appear appropriate, thus leaving $500K available to use for scope enhancements at this time. The project appears to have sufficient contingency to add the proposed Stage 1 inflector scope enhancement. The initial cost estimate appears credible, and the Committee agreed with the project’s plan to have an internal review to validate scope and cost once approved. This scope enhancement does not create additional schedule or cost risk to the current baselined scope. The project will need approval of the Stage 1 scope enhancement this month in order to complete the work within the early completion date. If the project runs into a situation where it needs additional cost contingency, the Stage 1 inflector work can be stopped anytime without jeopardizing the project KPPs.

The Committee commended the projects use of EVMS as a project management tool. The Control Account Managers (CAMs) are providing useful information and analysis to help successfully manage and complete the project. The Committee commended the project on actively managing risks. The remaining risks on the project appear comprehensive, complete, and well understood. The cost and schedule contingency available appear adequate to successfully complete the project.
The project is potentially a year away (March 2017) from achieving the KPPs for CD-4, but the project is entering its peak workload period, which continues through project completion. Significant effort and diligence to complete the work on schedule is needed in order to complete the project on the early completion timeframe. The project is now entering a crucial period where procurement and activity delays can potentially push back early project completion. Labor represents the majority of remaining cost so delaying project completion results in significant standing army costs (up to $200K a month in project management).

The project has also lost schedule contingency in many areas and activities, and all the major divisions (accelerator, SR, detectors) are either on critical path or near critical path. Once activities are near the critical path, those activities appear to receive more attention and resources. This may lead to parallel critical paths that are harder to manage, but the Committee judged there is ample schedule/cost contingency to handle the remaining issues/risks.

The unsuccessful Q1 Quadrupole prototype test will result in the project using the original Q1 plate, which causes a 20% loss in injection efficiency. This has no effect on cost/schedule and meeting the KPPs, but it does lengthen the operational time period.

Procurements are moving forward and many of the delays are due to extra time needed to prepare the requirements/specifications. None of the procurements appear to be delaying the early finish project schedule at this time. Continued management attention on the remaining procurements and proactively managing vendors will be essential to completing the project on the early finish schedule.

The accelerator work is on the critical path and represents approximately 60% of the remaining work. Continued management attention should be paid to this area so that laboratory resources and labor are made available for the successful initiation of the experiment.

4.3 **Recommendation**

4. Based on current project performance and available contingency, the Committee supported moving forward with adding scope enhancements up to $500K.
5. PROJECT MANAGEMENT

5.1 Findings

The g–2 project is currently 70% complete with the bulk of the remaining work primarily involving the Accelerator WBS.

The g–2 science collaboration currently includes 150 members at 35 institutions.

The February 2016 risk register includes 55 active risks. In the past there have been 3 realized and 11 retired risks.

The SR was installed in 2015. It was turned over to operations and brought to full power in September 2015.

The project received CD-2/3 in August 2015.

A helium leak was recently discovered in a lead can of the SR. The operations team is working on repair solutions that may have an effect on the project shimming efforts.

The project team is fully staffed.

The project anticipates carrying over between $1 million and $2 million of budget into FY 2017.

Fifteen baseline changes have been processed to date costing approximately $1.3 million.

Related AIP projects are on schedule and do not appear to add risk to the CD-4 date.

The recommendations from the previous reviews have been addressed.

Transition to Operations planning and scheduling efforts related to individual systems and components is beginning.

5.2 Comments

The Committee found the g–2 project team to be very capable, proactive, and committed.

The Committee was concerned about the minimal carry over into FY 2017. The program office confirmed that early funding of g–2’s FY 2017 $6.2 million budget is anticipated, which will mitigate the minimal carry-over risk.

Vigilance related to completing the remaining procurements on schedule and managing vendor delivery/performance is critical to the early delivery of g–2.

The Committee judged shared technician and magnet fabrication resources could be a challenge to complete the g–2 project on a schedule to support early science. Vigilance related to early
planning, communicating, and assigning Fermilab labor resources will be key to the experiments ability to collect early data.

The risk register appears to be appropriately developed and adequately managed.

Transition to operations and commissioning planning efforts are in the early stages and should be a high priority moving forward.

The Committee supported the concept of the new Inflector. The g–2 project should finalize planning related to the inflector design and construction to ensure it is prepared in time to support early science.

5.3 Recommendations

5. The g–2 project in consultation with the HEP Program Office should further evaluate the new inflector strategy.

6. Develop a detailed, integrated Transition to Operations Plan and schedule that includes all activities from commissioning through experiment start up (including accelerator readiness). Present the plan and schedule to the program office no later than June 30, 2016.
MEMORANDUM FOR STEPHEN MEADOR
DIRECTOR
OFFICE OF PROJECT ASSESSMENT

FROM:   MICHAEL PROCARIO
        DIRECTOR OF FACILITIES
        FOR HIGH ENERGY PHYSICS

SUBJECT: REQUEST TO CONDUCT INDEPENDENT PROJECT REVIEW
OF THE MUON g–2 PROJECT

FEB 17 2016

I am writing to request your Office of Project Assessment conduct an Independent Project Review of the Muon g–2 Project on April 6–7, 2016 at Fermilab. The purpose of the review is to assess the project’s status and progress since the June 2015 DOE review. As part of the assessment, your committee should address the following questions:

1. Are the planned Scope, Schedule and Estimate to Complete updated and credible, including any planned scope enhancements?

2. Has the risk analysis been updated to reflect the real risks for completing the project and are the contingencies acceptable?

3. Are there any significant risks that jeopardize CD–4 completion and require management attention?

As Program Manager for the Muon g–2 Project, Dr. Theodore Lavine will serve as the Office of High Energy Physics contact person for this review.

We appreciate your assistance in this matter. As you know, these reviews play an important role in our program. I look forward to receiving your Committee’s report.

cc: Patricia Dehmer, SC-2
    James Siegrist, SC-25
    Theodore Lavine, SC-25
    John Kogut, SC-25
    Paul Philp, FPD, FSO
    Nigel Lockyer, FNAL Director
    Michael Lindgren, FNAL Chief Project Office
    Chris Polly, Project Manager
    Michael Weis, Fermi Site Office Manager
Appendix B  Review Committee

DOE/SC Status Review of the Muon g-2 Project
April 6-7, 2016

Kurt Fisher, DOE/SC, Chairperson

SC1 Accelerator
* Rod Gerig, retired ANL
  Peter Ostroumov, ANL

SC2 Storage Ring
* Ross Schlaeter, LBNL
  Sasha Zholents, ANL

SC3 Technical Integration
* Soren Prestemon, LBNL
  Howard Gordon, BNL

SC4 Detectors
* Richard Kass, OSU

SC5 Cost and Schedule
* Jerry Kao, DOE/SC
  Ron Lutha, DOE/ASO

SC6 Project Management
* Jeff Sims, SLAC
  Steve Trotter, ORNL

Observers
Mike Procario, DOE/SC
Ted Lavine, DOE/SC
Petros Rapidis, DOE/SC
Bill Wisniewski, SLAC / DOE/SC

Pepin Carolan, DOE/FSO
Paul Philp, DOE/FSO

LEGEND
SC Subcommittee
* Chairperson

Count: 12 (excluding observers)
Appendix C     Review Agenda

DOE/SC Status Review of the Muon g–2 Project at Fermilab
April 6-7, 2016

AGENDA

Wednesday, April 6, 2016—Fermilab, Wilson Hall, Comitium

8:00 am Executive Session—Comitium (WH2SE) .................................................. K. Fisher
8:45 am Overview of Project and Performance—One West (WH1W) .................... C. Polly
9:30 am Accelerator, Muon Target Station, Beamline, ....................................... M. Convery
     Controls and Instrumentation
10:15 am Break—Outside of One West
10:30 am Overview of Muon Storage Ring, Injection and Shimming ...................... P. Winter
11:20 am Experimental Detectors ........................................................................... B. Casey
12:00 pm Lunch—Second Floor Cross Over
1:10 pm Review Photo—Atrium
1:20 pm New Proposed Inflector Design—One West (WH1W) ......................... V. Kashikin
2:00 pm Project Path Forward.............................................................................. C. Polly
2:50 pm Subcommittee Breakout Session
4:00 pm Committee Q&A with Project Team
5:00 pm Full Committee Executive Session
6:30 pm Adjourn

Thursday, April 7, 2016

8:00 am Subcommittee Breakout Session
10:00 am DOE Full Committee Executive Session—Dry Run............................. K. Fisher
12:00 pm Lunch
1:30 pm Closeout Presentation
2:30 pm Adjourn
## Appendix D  Muon g–2 Cost Table

<table>
<thead>
<tr>
<th>WBS: Control Account</th>
<th>BAC $M</th>
<th>CTG $M</th>
<th>% Comp</th>
</tr>
</thead>
<tbody>
<tr>
<td>1: Project Management</td>
<td>3.88</td>
<td>1.06</td>
<td>73%</td>
</tr>
<tr>
<td>2.1: Accelerator PM</td>
<td>2.59</td>
<td>0.70</td>
<td>73%</td>
</tr>
<tr>
<td>2.2: Target Station</td>
<td>1.66</td>
<td>0.77</td>
<td>54%</td>
</tr>
<tr>
<td>2.3: Beamlines</td>
<td>12.10</td>
<td>5.19</td>
<td>57%</td>
</tr>
<tr>
<td>2.4: Accel C&amp;I</td>
<td>1.69</td>
<td>0.52</td>
<td>69%</td>
</tr>
<tr>
<td>3.1: Ring PM</td>
<td>1.71</td>
<td>0.57</td>
<td>67%</td>
</tr>
<tr>
<td>3.2: Magnet</td>
<td>4.55</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td>3.3: Inflector</td>
<td>1.86</td>
<td>0.64</td>
<td>65%</td>
</tr>
<tr>
<td>3.4: Storage Ring Vacuum</td>
<td>1.25</td>
<td>1.00</td>
<td>20%</td>
</tr>
<tr>
<td>3.5: Kickers</td>
<td>1.45</td>
<td>0.40</td>
<td>73%</td>
</tr>
<tr>
<td>3.6: Quadrupoles</td>
<td>0.94</td>
<td>0.65</td>
<td>31%</td>
</tr>
<tr>
<td>3.7: Ring C&amp;I</td>
<td>0.92</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td>3.8: Precision Field</td>
<td>1.38</td>
<td>0.59</td>
<td>57%</td>
</tr>
<tr>
<td>4: Detectors</td>
<td>0.54</td>
<td>0.24</td>
<td>55%</td>
</tr>
<tr>
<td>5: Disassembly &amp; Trans.</td>
<td>4.18</td>
<td>0</td>
<td>100%</td>
</tr>
<tr>
<td>Total Project</td>
<td>40.72</td>
<td>12.35</td>
<td>70%</td>
</tr>
</tbody>
</table>
## Appendix E  
Muon g–2 Funding Table

<table>
<thead>
<tr>
<th></th>
<th>FY 2012</th>
<th>FY 2013</th>
<th>FY 2014</th>
<th>FY 2015</th>
<th>FY 2016</th>
<th>FY 2017</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>OPC-Other</td>
<td>0.601</td>
<td>2.742</td>
<td>3.20</td>
<td></td>
<td></td>
<td></td>
<td>6.543</td>
</tr>
<tr>
<td>OPC-Design</td>
<td>3.108</td>
<td>5.20</td>
<td>4.1</td>
<td></td>
<td></td>
<td></td>
<td>12.408</td>
</tr>
<tr>
<td>TEC-MIE</td>
<td></td>
<td>2.00</td>
<td>9.0</td>
<td>10.20</td>
<td>6.249</td>
<td></td>
<td>27.449</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>0.601</td>
<td>5.850</td>
<td>10.40</td>
<td>13.10</td>
<td>10.20</td>
<td>6.249</td>
<td>46.400</td>
</tr>
</tbody>
</table>
Appendix F  Muon g–2 Schedule Chart

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>Sep</td>
<td>Prepare vacuum chambers</td>
</tr>
<tr>
<td></td>
<td>Oct</td>
<td>Prepare old inflector/install infrastructure</td>
</tr>
<tr>
<td></td>
<td>Nov</td>
<td>Prepare quads</td>
</tr>
<tr>
<td></td>
<td>Dec</td>
<td>Field Shimming</td>
</tr>
<tr>
<td>2016</td>
<td>Jan</td>
<td>Install/Test old inflector</td>
</tr>
<tr>
<td></td>
<td>Feb</td>
<td>Final test quads</td>
</tr>
<tr>
<td></td>
<td>Mar</td>
<td>Install Chambers</td>
</tr>
<tr>
<td></td>
<td>Apr</td>
<td>Prepare kickers</td>
</tr>
<tr>
<td></td>
<td>May</td>
<td>Prepare field equipment</td>
</tr>
<tr>
<td></td>
<td>Jun</td>
<td>Prepare detectors/electronics/DAQ</td>
</tr>
<tr>
<td></td>
<td>Jul</td>
<td>Install kickers, field monitoring equipment, det/elec/DAQ</td>
</tr>
<tr>
<td></td>
<td>Aug</td>
<td>He leak repair (off project)</td>
</tr>
<tr>
<td></td>
<td>Sep</td>
<td>Beamline construction</td>
</tr>
<tr>
<td>2017</td>
<td>Oct</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Nov</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dec</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Jan</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Feb</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mar</td>
<td></td>
</tr>
</tbody>
</table>
Appendix G  Muon g–2 Management Chart