Issues Associated with the Coordination of the Mu2e and Muon g-2 Experiments

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# Overview

The new Muon g-2 experiment is proposed to run at Fermilab[[1]](#footnote-1) using largely preexistent accelerator facilities and using a new building to house the experiment’s superconducting muon storage ring. The g‑2 experiment will run concurrently with the NOA experiment and will alternate running periods with the Mu2e experiment.

While running, the g-2 experiment plans to use six Booster proton batches each super-cycle[[2]](#footnote-2). When NOA is running, this leaves two empty batches per super-cycle[[3]](#footnote-3). Micro-BooNE, NOA, and g-2 cannot run simultaneously at their respective design rates. The g-2 experiment expects to receive a total of 4×1020 protons on target (POT) over the lifetime of the experiment.

8 GeV kinetic energy proton beam designated for the g-2 experiment is injected into the Recycler via the NOA injection line; there, it undergoes RF manipulations and is ultimately extracted by way of the (presently non-existent) Mu2e Recycler-to-P1 beamline to what is currently the pbar production target. 3.1 GeV/c secondaries are collected from the target and transported to the Debuncher Ring. The beam takes a partial turn in the Debuncher and is then transported to the g-2 facility where it is injected into a superconducting muon storage ring. By the time the secondary beam reaches the muon storage ring, very nearly all beam particles, except the muons (and a small number of*p*’s and *e*+’s), have decayed. Thus, the beam delivered to the g-2 muon storage ring is a fairly pure muon beam.

For the Mu2e experiment, the 8 GeV protons take only a partial turn in the recycler before they are extracted and transported to the Accumulator ring. Protons are stacked and undergo a sequence of RF manipulations in the Accumulator. The proton beam is then synchronously transferred to the Debuncher where it is resonantly extracted into a new beamline that transports it to the Mu2e production target.

Both the Muon g-2 and the Mu2e experiments plan to use the present Antiproton Source complex with a number of upgrades and modifications. This document is an attempt to compile a list of the significant issues, that have already been identified, associated with the incorporation of the g-2 experiment into the near term future of accelerator operations at Fermilab.

# Proton Source Issues

The successful coordination of the NOA, Micro-BooNE, Mu2e, and Muon g-2 experiments depends on the success of the Proton Source Upgrades that are presently underway. For simultaneous NOA and g‑2 running, or for simultaneous NOA and Mu2e running, the Booster must be capable of delivering 4×1012 protons/batch at a rate of at least 13.5 Hz.

Both the Mu2e and g-2 experiments are sensitive to the longitudinal emittance of the proton batches from the Booster. Presently the Mu2e experiment assumes that this longitudinal emittance will be no greater than 0.12 eV-sec per 53 MHz bunch. The g-2 experiment assumes a longitudinal emittance of 0.07 eV‑sec.

The Booster, MI8 beamline, Recycler, pbar beamlines, and Debuncher ring are all slightly mismatched in energy. The degree to which this affects the g-2 experiment has not yet been assessed.

# Recycler Issues

In the Recycler, a g-2 batch is re-bunched with a 2.5 MHz RF system[[4]](#footnote-4). The purpose of this manipulation is to produce a train of four proton bunches, each of which is very narrow in time. As the beam tumbles in these RF buckets, it is extracted, one bunch at a time, in intervals of half the synchrotron period (~12 msec). Extraction must be synchronized with the synchrotron motion of the beam such that a bunch is extracted when the time width is at a minimum and the energy spread is at a maximum. Each of the extracted bunches is expected to have an rms pulse length of not more than ~50 nsec.

There are a number of issues with the planned muon g-2 use of the Recycler Ring:

* There are three significant issues associated with the RF manipulations in the Recycler.
  + The first issue is that of achieving the narrow pulse width required by the experiment. The requirement to narrow the pulse to less than 50 nsec rms requires more RF voltage than the existing systems possess. It is important to maintain a small pulse width not only to meet the requirements of the g-2 experiment, but also to allow more time for the extraction kicker voltage rise. Any beam in the tails of the pulse time distribution will likely be lost in the Recycler, contributing to increased radiation levels. The achievable pulse width in the presence of realistic emittance diluting effects (beam loading, impedance, and noise) and with larger Booster longitudinal emittances has not yet been studied.
  + The second Recycler RF issue is that of the momentum spread of the extracted beam. This momentum spread must be smaller than the momentum aperture of the Recycler and the transport beamlines to the target. With large Booster longitudinal emittances, this constraint could limit the amount by which the pulse length can be narrowed. This is definitely a matter for further study.
  + Finally, the third Recycler RF issue is beam loading of the 2.5 MHz and 53 MHz resonant RF cavities in the Recycler. Large transient beam loading will likely require augmentation of the RF systems with feed forward or a combination of feed forward and feedback. This also is a matter that has yet to be studied.
* The installation of the RF systems for g-2 would require a long (months) interruption of the NOA program.
* The RF equipment in the Recycler requires a substantial service building footprint. All of the space presently used for RF has already been designated for systems that support NOA. A determination of where the g-2 Recycler RF equipment is to be located should be undertaken very soon since a new service building or expansion of an existing service building may be required.
* Recycler injection and extraction:

For both Mu2e and muon g-2, beam transfer from the Booster to the Recycler is facilitated by a beamline stub and kicker that will be installed for the NOA experiment. Mu2e must inject and extract their proton batches to and from the Recycler in the presence of circulating proton batches that are designated for NOA. g-2 beam in the Recycler ring will always consist of only one circulating batch. For both experiments, extraction will require an additional kicker in the vicinity of MI52 and a new beamline stub that connects the Recycler Ring to the existing P1 beamline.

g-2 beam is extracted one bunch at a time at a rate of one bunch every 12 msec following the RF manipulations in the Recycler. To achieve this, the Recycler extraction kicker must have a rise time that is much smaller than the bunch spacing (~200 nsec – leading edge to trailing edge), and have a burst rate of at least 1/12 msec = 83.3 Hz.

Mu2e plans to use a kicker built from the Main Injector gap-clearing kicker design, which has a rise and fall time of 57 nsec. This rise and fall time meets the requirements of both experiments. However, the ability of this kicker to provide burst repetition rates of 83.3 Hz has yet to be determined. Moreover, since the 12 msec extraction interval is tied to the synchrotron period of the bunched beam, the required repetition rate may go even higher if the RF voltage must be increased to meet the g-2 pulse length requirements.

# Recycler to AP1 Transport

Both experiments utilize the existing Antiproton Source beamlines to transport beam from the Recycler Ring. Plans to build a beamline stub from the Recycler to the P1 beamline and upgrade the P1 and AP1 beamlines are presently part of the Mu2e project. Also included in this work are plans to expand the MI52 service building to accommodate the pulsed power supply equipment necessary for the Recycler extraction kicker[[5]](#footnote-5). The earliest approval and funds could be received to begin this work is after the Mu2e experiment receives CD-3a[[6]](#footnote-6), which is projected to be in early 2013. In any schedule that has a g-2 run prior to initial Mu2e running, this is a very late start. The present g-2 thinking is that an AIP project that includes the Recycler extraction kicker and beamline stub might be approved sooner. If this is indeed the plan, it must be implemented very soon.

Installation of the Recycler to P1 beamline equipment would necessitate a NOA shutdown. Since this beamline is to be used for both Mu2e and g-2, this is a shutdown that will be required even if the g-2 experiment does not run before the first Mu2e run.

# Antiproton Source Target station

The Mu2e experiment does not use the Antiproton Source target station. The g-2 experiment, however, will use at least part of this facility to produce its 3.1 GeV/c muon beam. This is an area that requires serious attention very soon. The various issues associated with the target station are listed below.

* The g-2 experiment has not yet determined which pbar target station components will be reused and which will be replaced. There is a lot at stake here. There are significant space constraints. Some plans envisioned by g-2 experiment will require a relocation of the target from the Target Vault to the downstream end of the Pre-Vault beam enclosure.
* If the g-2 experiment opts to use existing pbar pulsed target station equipment, it is likely that the existing pulsed power supplies will not be capable of the large repetition rates required by the g-2 experiment.
* The equipment that has been suggested so far to replace Pbar target station components is very likely not compatible with the present scheme of mounting modular target station elements. A redesign of the target station support system is a significant mechanical engineering undertaking.
* In the present antiproton production mode, the beamline from the target to the end of the dump (~7.25 m) is at atmospheric pressure. The g-2 experiment would like to have this either placed under vacuum or filled with a lighter gas (He). Every method for accomplishing either of these that has been suggested to date has been shown to be unworkable.
* The pion collection efficiency critically depends on whether or not the existing lithium lens can be used and its operational limitations if it is used. The alternative to the lithium collection lens consists of conventional quadrupole magnets[[7]](#footnote-7). Simple scaling calculations performed a year and a half ago suggest that the present lens design could withstand the estimated g-2 heat load if the gradient is limited to half (½) of the present focusing strength. A serious engineering analysis must be undertaken very soon to determine the feasibility of using the lithium lens.
* There are issues associated with the experiment’s desire to run with both negatively and positively charged muons. For example, the primary proton beam must hit the target dump sufficiently close to its axis for both polarities.
* The planning for all of this will require a significant amount of effort from Accelerator Division Mechanical and Electrical engineers. There is a significant amount of work here for Pbar department physics staff as well. This work must start very soon. These are the very same engineering and scientific resources of which the Mu2e experiment is in desperate need.

# Beam transport from the target and the Debuncher

There are presently two options under consideration for where the g-2 secondary beam goes downstream of the target. The original scenario proposed by the g-2 experiment uses a modified AP2 beamline to transport 3.1 GeV/c secondaries from the target to the Debuncher at location D50. This is the same path presently used in antiproton production. In this scenario, the secondary beam takes a partial turn in the Debuncher and is directed into a modified AP3 beamline where it ultimately is injected into the muon storage ring located south of the present AP0 service building.

The second scenario (called the “Muon Campus” option) uses a modified AP3 line to transport secondary beam from the target to the Debuncher at location D30. In this scenario, the secondary beam takes one turn around the Debuncher and is extracted again at D30 using the Mu2e external beamline. This scenario locates the g-2 building approximately in the parking lot across the street from the West Booster Towers.

Both of these scenarios are fraught with peril. In both scenarios the AP3 beamline and/or the AP2 beamline require substantial modification from their present configuration.

The issues associated with each of these two scenarios are listed here.

## Original Scenario

There are a number of issues that arise in the original g-2 scenario.

* The g-2 experiment’s use of the AP2 line to transport secondaries to the Debuncher conflicts with the Mu2e plans to use the downstream end of this line for transport to the Debuncher abort beam dump. This part of the AP2 beamline is very compact and several beamline elements are difficult (not impossible) to get at. Recurrent conversion of this part of AP2 from/to a g-2 configuration to/from a Mu2e configuration will be difficult.
* The g-2 experiment wishes to greatly multiply (2 to 3×) the quadrupole magnet density along the AP2 line. This seems to be possible for the upstream end of the beamline. However, the bending section (the “left bends”) and the downstream end of the line are so heavily populated with magnets that the addition of more quadrupole magnets seems very difficult or impossible.
* Power supplies for the extra quadrupole magnets could primarily be located in the AP0 service building where there is no competition with Mu2e for space. However, if there are power supplies to be added for more quadrupoles in the downstream end of AP2, these may have to be located in the AP50 service building. Mu2e will likely need most (probably all) of the available space in AP50 for new RF equipment.
* The Mu2e experiment plans to use the 6-4-120 dipoles that constitute the bending section of the AP2 line for the bending section of the new Mu2e external beamline. Thus, if g-2 uses the AP2 line, Mu2e will incur the extra cost of building these magnets. There are also several AP2 line quadrupoles that Mu2e is planning to have available for its external beamline. Mu2e costs for the external beamline magnets and power supplies will be affected if AP2 line magnets are not available for use.

One could think of moving magnets and power supplies back and forth between the AP2 line and the Mu2e external beamline for each Mu2e to g-2 turnover. This would complicate and extend the time required for the changeover. The resources required to accomplish these moves would add to the cost of each changeover. Moreover, re-installing this many beamline elements would probably lengthen the time required to re-commission the facility for each new mode of operation.

* Any work on the transport enclosure part of the AP2 beamline precludes running beam in the MI8 beamline (which passes below the transport enclosure). This obviously turns off NOA.
* This scenario uses a modified AP3 line to transport beam from the Debuncher to the g-2 storage ring. The Mu2e experiment plans to use the AP3 beamline for beam transport to the Accumulator. Consequently the optics requirements of each experiment are rather different. However, an AP3 line that meets the requirements of the g-2 experiment should also be generally adequate for Mu2e purposes. There are, however, several issues that remain:
  + Mu2e requires that the AP3 line connect to the Accumulator, g-2 wants the AP3 line to connect to the Debuncher. Therefore, the rings side of the AP3 line must be significantly reconfigured when changing operating modes from/to g-2 to/from Mu2e.
  + This reconfiguration is complicated by the fact that Mu2e extraction also occurs in the D30 section of the Debuncher (long straight section under the AP30 service building). The Mu2e extraction septum and lambertson are expected to be heavily shielded and very radioactive. Thus, greatly complicating the reconfiguration of the AP3 beamline.
* In this g-2 scenario, the AP3 line bypasses the target station bringing beam into the pre-vault enclosure. From there the beam must, in a very small space, be redirected vertically and horizontally to the g-2 storage ring at ground level. There are several problems with this that must be overcome:
  + There is no room in the target bypass for any beamline elements – it can only be a drift. It will be a challenge to maintain the 35  mm-mrad aperture through this section and/or to match this section into the complicated bending section that immediately follows.
  + The AP3 line is presently at the same height as the AP1 line (near the enclosure ceiling). Thus, the AP1 line presents a significant interference to the transport of beam from the AP3 line to the g-2 storage ring.
  + Some knowledgeable people have expressed reservations about having a muon beamline with an upward vertical component.
  + The civil construction implementing beam transport past the target and up to the muon storage ring will require a shutdown of SY120.
* The g-2 experiment plans to increase the focusing of the AP3 beamline. All of the power supplies for the new magnets in the upstream end of the line would have to be located in the AP30 service building. Mu2e plans to use all of the AP30 service building for RF, kicker power supplies, and external beamline power supplies – there is no space available for extra AP3 line power supplies.

## Muon Campus Scenario

There are also several issues associated with the so-called Muon Campus scenario.

* The shielding around the existing pbar target dump will have to be modified to accommodate an AP3 line that transports secondaries from the target. This is a high radiation area so this work will require careful planning.
* In this scenario, both Mu2e and g-2 perform injection and extraction in the same straight section. The g-2 experiment is doing injection and extraction from the same section of one machine – the Debuncher. The 30 straight section area of the Pbar rings enclosure in this scenario becomes a very complicated place. A 3-D model of this area should be constructed to assist design work and to verify the non-interference of all of the beamline components in this area.
* The 30 straight-section will be a high radiation area due to beam loss from resonant extraction during Mu2e operation. Long cool down periods will be required prior to any work in the 30 straight-section once Mu2e begins operation. Since this is an area of especially egregious interfaces between g-2 and Mu2e, the process of converting from one mode of operation to the other with be delayed, extended, and complicated by radiation safety issues.
* The aperture of the Mu2e external beamline is probably less than the 35  mm-mrad that the g-2 experiment requires. In particular, the upstream horizontal bending section of the Mu2e beamline uses dipoles with a 3 inch vertical aperture (converted 6-4-120 dipoles). The vertical beta-functions in this section are large (>30 m). Consequently, the vertical aperture in this section drops to about 12 . There may be some room to modify the optics of this section to lower the vertical beta-function somewhat. However, it is very likely that a different dipole with a wider vertical aperture would need to be designed and built. Such a magnet would require more power to achieve the same field with a wider pole separation. Present plans to use the 6-4-120 dipoles from the AP2 line left bend probably will not meet the requirements of the g-2 experiment.
* Since a significant portion of the AP3 beamline lies within the Pbar Transport enclosure, much of the mode changing work will interrupt NOA operations.
* In this scenario, the g-2 experiment also plans to increase the focusing in the external beamline. All of the power supplies for the new quadrupole magnets would have to be located at the AP30 service building. Mu2e’s plans exhaust all of the available space in the AP30 service building.
* Injection and extraction to/from the same straight section in the same ring is problematic.
* The final muon beam to the g-2 storage ring has a vertical component and points in the general direction of the Science Education Center.
* There is some controversy over whether or not the fields from the Mu2e extinction AC dipole and/or the solenoids affect the precision field in the muon storage rings. Will Mu2e be able to excite these dipoles for testing purposes during g-2 running?

## Issues Common to both Scenarios

* When changing operating modes from Mu2e to g-2, it is almost certain that we will need to move the Mu2e Debuncher extraction septum and lambertson out of the beamline because they will be aperture limitations for g-2. These devices will be very radioactive after Mu2e running, complicating a subsequent return to g-2 running.
* The aperture requirements for the g-2 experiment are more stringent than those for Mu2e. This places constraints on the design of Debuncher equipment for Mu2e that are not yet well understood. The options available for each Mu2e device that is a potential limiting aperture for g‑2 are to design the device with a larger aperture (which makes it more expensive) or replace the device with a spool piece during g-2 operation (complicates mode changes, radiation safety issues).
* Each change of mode from Mu2e to g-2 and visa-versa requires a change in the operating energy of the Debuncher. Both energies are well within the range of existing Antiproton Source power supplies. However, changing the operating energy will complicate re-commissioning and probably lengthen the first few re-configurations until procedures can be perfected.
* In order to retain as many high amplitude pions as possible until they decay[[8]](#footnote-8), the g-2 experiment plans to greatly increase the focusing in these beamlines. This adds significantly to the number of quadrupoles in each beamline, which in turn adds associated power supply (service building space) and cooling requirements (CUB capacity). These extra quads also cause service building space issues in some locations.

# Debuncher Issues

* The g-2 experiment plans to use a Lambertson magnet for injection into the Debuncher (whether from AP2 or AP3). The experiment requires that a 35  mm-mrad (absolute) aperture be maintained all the way to the storage ring inflector. This will be a difficult (perhaps impossible) magnet to build.
* The g-2 has been discussing the possibility of tuning the operating point of the Debuncher to a horizontal half-integer resonance. Done correctly, this would automatically place the beam in the extraction channel after one turn around the Debuncher. While clever, this technique costs aperture. When the beam is not steered to the central orbit, it is closer to horizontal aperture limits.

# General Issues

* The central orbit beam energy of the MI-8 beamline, Recycler, and Debuncher are different. There is a plan to correct for this that works for Mu2e operations. It is not yet clear that this plan is sufficient for g-2 as well.
* As a consequence of the Director’s technical review of early May 2011, Mu2e is in the process of determining locations for all of the equipment added for the Mu2e experiment. The fact that g-2 requires some of the available space in a way that is largely unknown compromises Mu2e’s equipment location determination.
* Much of the installation of equipment for Mu2e precludes g-2 running and shortens the length of g‑2 running prior to the first Mu2e run. In particular, the shielding upgrades for the pbar service buildings required for Mu2e operation will prohibit beam operation in the Rings enclosure for as long as a year. This has not been shown on any lab schedule presented to date.
* Will the instrumentation installed for Mu2e 8 GeV protons be compatible with the g-2 instrumentation requirements for 3.1 GeV/c secondaries?
* Will a muon beam abort be required for the g-2 experiment? If so, where will it be located?

# Acknowledgements

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1. FNAL proposal P-989 [↑](#footnote-ref-1)
2. This is identical to the Mu2e proton scenario [↑](#footnote-ref-2)
3. 12 for NOA + 6 for Mu2e + 2 empty = 20 batches/super-cycle [↑](#footnote-ref-3)
4. C. Bhat, J. MacLachlan, “RF Requirements for Bunching in the Recycler for Injection into the g-2 Ring,” Beams-doc-3192 (28 August 2008). [↑](#footnote-ref-4)
5. There are no additional cable penetrations required for this MI-52 service building expansion. [↑](#footnote-ref-5)
6. Only limited construction is authorized at CD-3a. If authorization doesn’t come until CD-3b, work on beam transport from the Recycler could not start until early 2014. [↑](#footnote-ref-6)
7. The BNL g-2 experiment target station used DC conventional quads to collect secondaries from the production target. [↑](#footnote-ref-7)
8. Some of the high amplitude pions will decay into muons that are within the acceptance of the g-2 storage ring. [↑](#footnote-ref-8)