1 Accelerator and Muon Delivery

In order to achieve a statistical uncertainty of 0.1 ppm, the total g-2 data set must contain at least 1.8×10^{11} detected positrons with energy greater than 1.8 GeV, and arrival time greater than 30 μs after injection into the storage ring. This is expected to require 4×10^{20} protons on target including commissioning time and systematic studies. For optimal detector performance, the number of protons in a single pulse to the target should be no more than 10^{12} and the number/fraction(?) of secondary protons transported into the muon storage ring should be less than ??. Data acquisition limits the time between pulses to be at least 10 ms. The revolution time of muons around the storage ring is 149 ns, and therefore the experiment requires the bunch length to be roughly 100 ns. Systematic effects on muon polarization limit the momentum spread dp/p of the secondary beam. Requirements and general accelerator parameters are given in Table 1.

Parameter	Design Value	Requirement	Unit
Total protons on target	2.3×10^{20}/year	4×10^{20}	protons
Interval between beam pulses	≥ 10	≥ 10	ms
Max bunch length (full width)	120 (95%)	< 149	ns
Intensity of single pulse on target	1	1	Tp
Max Pulse to Pulse intensity variation	± 10	± 50	%
dp/p of pions accepted in decay line	2-5	2	%
Momentum of muon beam	3.094	3.094	GeV/c
Stored muons per proton on target	10^5 into inflector	≥ 6000	muons/Tp
dp/p of muons into ring	0.5	0.5	%
Fraction of beam into ring which is protons	1??	< 10??	%

Table 1: General beam requirements and design parameters.

1.1 Overall Strategy

The g-2 experiment at Fermilab is designed to take advantage of the infrastructure of the former Antiproton Source, as well as improvements to the Proton Source and the conversion of the Recycler to a proton-delivery machine. It is also designed to share as much infrastructure as possible with the Mu2e experiment in order to keep overall costs low.

The Antiproton Accumulator will no longer be in use, and many of its components will be reused for the new and redesigned Muon beam lines. Stochastic cooling components and other infrastructure no longer needed in the Debuncher ring will be removed in order to improve the aperture, proton abort functionality will be added, and the ring will be renamed the Delivery Ring (DR). The former AP1, AP2, and AP3 beam lines will be modified and renamed M1, M2, and M3. The DR Accelerator Improvement Project (AIP) will provide upgrades to the Delivery Ring as well as aperture improvements to the P1, P2, and M1 lines needed for future muon experiments using 8 GeV protons, including g-2. The layout of the beam lines is shown in Fig. 1.

Figure 1: Path of the beam to g-2.

The Proton Improvement Plan [1], currently underway, will allow the Booster to run at 15 Hz, at intensities of 4×10^{12} protons (4 Tp) per Booster batch. Following the completion of the Accelerator and NuMI Upgrades (ANU) subproject at Fermilab to prepare for the NOνA experiment [2], the Main Injector (MI) will run with a 1.333 s cycle time for its neutrino program, with twelve batches of beam from the Booster being accumulated in the Recycler and single-turn injected at the beginning of the MI cycle. While the NOνA beam is being accelerated in the MI, eight Booster batches will be available for experimental programs such as g-2 which use 8 GeV protons. The ANU subproject will also enable injection from the Booster into the Recycler. Extraction from the Recycler to the P1 beam line, required for g-2, will be implemented in the Recycler AIP.

Protons from the Booster with 8 GeV kinetic energy will be re-bunched into four smaller bunches in the Recycler and transported through the P1, P2, and M1 beam lines to a target at AP0. Secondary beam from the target will be collected using a focusing device, and positively-charged particles with a momentum of 3.11 GeV/c will be selected using a bending magnet. Secondary beam leaving the target station will travel through the M2 and M3 lines which are designed to capture as many muons with momentum 3.094 GeV/c from pion decay as possible. The beam will then be injected into the Delivery Ring. After several revolutions around the DR, essentially all of the pions will have decayed into muons, and the muons will have separated in time from the heavier protons. A fast kicker will then be used to abort the protons, and the muon beam will be extracted into the new M4 line, and finally into the new g-2 beam line which leads to the g-2 storage ring. Note that the M3 line, Delivery Ring, and M4 line are also designed to be used for 8 GeV proton transport by the Mu2e experiment.

The expected number of muons transported to the storage ring, based on simulations assuming the target design used for antiproton production, is 1×10^5???. The simulation modeled the preferred alternatives discussed in the following sections. More details are given in Sec. 1.9.

Beam tests were conducted using the existing Antiproton-Source configuration with total charged-particle intensities measured at various points in the beamline leading to the Debuncher, which confirmed the predicted yields to within a factor of two(???) [3].

1.2 Protons from Booster

During the period when g-2 will take data, the Booster is expected to run with present intensities of 4×10^{12} protons per batch and with a repetition rate of 15Hz. In a 1.333s Main-Injector super cycle, twelve Booster batches are slipstacked in the Recycler and then accelerated in the MI and sent to NOνA. While the Main Injector is ramping, a time corresponding to eight Booster cycles, the Recycler is free to send 8 GeV (kinetic energy) protons to g-2. The RF manipulations of beam for g-2 in the Recycler (Sec. 1.3.1) allow g-2 to take four of the eight available Booster batches. Figure 2 shows the time structure of beam pulses to g-2.

Figure 2: Time structure of beam pulses to g-2.

The following section describes improvements needed to run the proton source reliably at 15Hz.

1.2.1 Proton Improvement Plan

The Fermilab Accelerator Division has undertaken a Proton Improvement Plan (PIP) [1] with the goals of maintaining viable and reliable operation of the Linac and Booster through 2025, increasing the Booster RF pulse repetition rate, and doubling the proton flux without increasing residual activation levels.

The replacement of the Cockroft-Walton pre-accelerator with an RFQ during the 2012 shutdown is expected to increase reliability of the pre-accelerator and to improve beam quality.

The Booster RF solid state upgrade is necessary for reliable 15 Hz RF operations. This involves the replacement of 40-year-old electronics that are either obsolete, difficult to find, or unable to run at the required higher cycle-rate of 15 Hz, and will allow for easier maintenance, shorter repair times, and less radiation exposure to personnel. The solid state upgrade will be completed in 2013.

Refurbishment of the Booster RF cavities and tuners, in particular, cooling, is also necessary in order to operate at a repetition rate of 15 Hz.

Other upgrades, replacements, and infrastructure improvements are needed for viable and reliable operation. Efforts to reduce beam loss and thereby lower radiation activation include improved methods for existing processes, and beam studies, for example, aimed at finding and correcting aperture restrictions due to misalignment of components.

The proton flux through the Booster over the past two decades and projected into 2016 based on expected PIP improvements is shown in Fig. 3.

Figure 3: Yearly and integrated proton flux (including PIP planned flux increase).

The new PIP flux goal will double recent achievements and needs to be completed within five years. Figure 4 shows both the increase in flux as well as planned users. The goal of doubling the proton flux will be achieved by increasing the number of cycles with beam. The intensity per cycle is not planned to increase.

Figure 4: Proton Source proton flux ramp up expectations for Intensity Frontier.

1.3 Recycler

The g-2 experiment requires a low number of decay electrons in a given segment of the detector, and therefore requires that the full-intensity (4×10^{12} protons) bunches be redistributed into four bunches of 1×10^{12} protons. These bunches should be spaced no closer than 10 ms to allow for muon decay and data acquisition in the detector. Because the revolution time of muons in the g-2 ring is 149 ns, and the time needed for the ring kicker to fire is XX, the longitudinal extent of the bunches should be no more than 120 ns. The Recycler modifications needed to achieve these requirements will be made under the Recycler AIP, and are described below.

1.3.1 Recycler RF

The proposed scheme for g-2 bunch formation [4] uses one RF system, 80 kV of 2.5 MHz RF. The design of the RF cavities will be based on that of existing 2.5 MHz cavities which were used in collider running, but utilizing active ferrite cooling. The ferrites of the old cavities and the old power amplifiers will be reused in the new system.

In order to avoid bunch rotations in a mismatched bucket, the 2.5 MHz is ramped "adiabatically" from 3 to 80 kV in 90 ms. Initially the bunches are injected from the Booster into matched 53 MHz buckets (80 kV of 53 MHz RF), then the 53 MHz voltage is turned off and the 2.5MHz is turned on at 3 kV and then ramped to 80 kV. The first 2.5 MHz bunch is then extracted and the remaining three bunches are extracted sequentially in 10 ms intervals. The formation and extraction or all four bunches takes two Booster ticks or 133 ms. This limits the g-2 experiment to using 4 of the available 8 Booster ticks in every Main Injector super cycle.

Simulated 2.5 MHz bunch profiles are shown in Fig. 5. The 53 MHz voltage was ramped from 80 to 0 kV in 10 msec and then turned off. The 2.5 MHz voltage was snapped to 3 kV and then adiabatically raised to 80 kV in 90 ms. The overall efficiency is 95%, and 95% of the beam captured is contained within 120 ns. The maximum momentum spread is $\Delta p/p = \pm 0.28\%$.

Figure 5: Results of RF simulations: 2.5 MHz voltage curve (upper left), phase space distribution (upper right), phase projection (lower left) and momentum projection (lower right).

Although the Recycler is not yet configured to do such RF manipulations, by using the 2.5 MHz coalescing cavities in the Main Injector, the proposed bunch formation scheme was tested with beam. In general, the agreement between simulations and data is very good. For illustration, the comparison between the beam measurements and the simulations for the case in which the 2.5 MHz voltage is ramped “adiabatically” from 3-70 kV in 90 ms is shown in Fig. 6.

Figure 6: Comparison of beam profile (left) with simulation (right) for the case in which the 2.5 MHz voltage is ramped “adiabaticatically” from 3-70 kV in 90 ms. In both profiles 95% of the particles captured are contained within 120 ns.

1.3.2 Recycler to P1 line connection

A new transfer line for 8 GeV kinetic energy protons from the Recycler ring to the P1 beamline will be constructed under the Recycler AIP. The P1 line is lower in elevation than the Recycler ring. Thus, a horizontal kick (traditional kicker) and a vertical bend (Lambertson magnet) will be used to extract the beam from the Recycler ring. Due to space limitations, only two bending centers are used. A vertical bending magnet is used to bend the beam into the center of the P1 line. An integer multiple of 360° in betatron phase advance between the two bending centers is required to cancel the vertical dispersion after bending down and up. Figure 7 shows the layout of the proposed transfer line from the Recycler Ring to the P1 beamline which has a total length of about 43 m. More details are given in [5].

Figure 7: Schematic layout of the transfer line from the Recycler Ring to the P1 line.

1.3.3 Recycler extraction

1.4 Proton transport beam lines

1.5 Target station

1.6 Pion to muon decay beam lines

1.7 Delivery Ring

1.8 Muon transport to storage ring

1.9 Simulation and expected muon rate into the storage ring

Location	Protons (10^5)	Pions (10^5)	Primordial Muons (10^5)	Decay Muons (10^5)	Ave. Muon Polarization
Start of M2 line	?	?	?	?	?
End of M3 line	?	?	?	?	?
Injected into Delivery Ring	?	?	?	?	?
In DR just before extraction	?	?	?	?	?
Extracted in M4 line	?	?	?	?	?
Just before inflector	?	?	?	?	?

Table 2: Expected beam intensities from simulation for 10^{12} protons on target.

1.10 Controls and beam monitoring

1.11 Radiation Safety Plan

1.12 ES&H, Quality Assurance, Value Management

References

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