Beams-doc-3220
version 0

Preparation of Accelerator Complex for Muon Physics Experiments at Fermilab

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25 September 2008

Abstract

The possible use of existing Fermilab facilities to provide beams for two muon experiments, namely the Muon to Electron Conversion Experiment and the Muon g-2 Experiment, is under consideration. A possible "Project X" could incorporate these experiments sometime in the future. However, the goals of the program being discussed in this note would be to perform these experiments following the completion of Run II with no impact to the on-going neutrino program by using spare Booster cycles to provide 8 GeV protons on target, and to do so with minimal cost to the Fermilab accelerator infrastructure. This document is meant to describe the present state of understanding of the recommended operational scenarios, work to be performed to bring to fruition, and first-pass cost estimates and schedules for the elements involved.

This is a working document, to be updated as further information is generated and understood. As the cost estimates and scheduling impacts are being worked on at present, it is hoped that this first version will help illuminate the current strategy being explored, particularly with committees and collaborations meeting in the near future. Many others are contributing to the effort described within, and are referenced, hopefully appropriately, throughout the document.

Contents

1 Preface

The Proton Plan and the NOνA Project will allow the Main Injector to run with a 1.333 sec cycle time for its neutrino program (NuMI), with twelve batches of beam from the Booster being accumulated in the Recycler and single-turn injected at the beginning of the MI cycle. Thus, there remain eight Booster cycles during each MI period that could in principle be used for an 8 GeV (kinetic energy) beam experimental program. Under the Proton Plan[1], the maximum average Booster repetition rate has been increased from roughly 2.5 Hz to 9 Hz. While not required for the NuMI program, a further upgrade to the Booster RF system remains necessary to allow the Booster to run at its maximum rate of 15 Hz and is discussed below. In subsequent sections we will assume this has been performed. Additionally the per cycle intensity may be greater with these upgrades, but for purposes of this discussion we will use a typical 4×10^{12} protons (4 Tp) per Booster cycle.

One experiment, the Muon to Electron Conversion Experiment ($\mu 2e$), has been given relatively high priority by HEPAP and would take several years to construct. Meanwhile, during the time period between when the Tevatron Run II program is concluded and $\mu 2e$ begins, much of the same facility components can be used to furnish beam to the other proposed experiment, the Muon g-2 Experiment (g-2) which would be relocated from Brookhaven National Laboratory. In what follows we look at each experiment's beam requirements and discuss how the Fermilab complex could readily meet those needs. The scenario proposed closely follows many of the concepts outlined in various talks and reports that have been around since 2006.[2] As presently understood, the g-2 experiment would be most likely to come on line first. Thus, it is discussed first in this document. It should be pointed out, however, that the two experiments could run independently in either order or, in principle, could be made to run in an interleaved fashion, the details of which are left to further investigations.

In the final section, we tabulate the required changes to the complex and formulate a first-order cost estimate.

1.1 Common Ground

Any further practical use of the Booster for an 8 GeV high intensity program will require the synchrotron to run at a 15 Hz repetition rate. In recent years the philosophy of Booster upgrade plans has been to upgrade components for full 15 Hz operation. In so doing, the current upgrades allow up to 9 Hz operation, and upgrades planned for NOνA will bring this number to 10.5 Hz. The remaining component upgrades necessary for true 15 Hz operation lie in the Booster RF system. In particular,

- The end cones of the ferrite-loaded tuners in the 19 Booster RF cavities will overheat at rates in excess of about 10 Hz. These cones have cooling channels, but these will need to be reconnected with the LCW system, and in some cases leaks will have to be repaired.
- Roughly half of the "bias supplies", which provide the current to modify the resonant frequency of

the Booster cavities, have transformers which are inadequate for 15 Hz operation. These supplies will need to be retrofit with more robust transformers.

- The two large anode supplies, which power all of the anodes of the RF power ampliers, will probably need to be upgraded with more robust transformers.

These upgrades are required for meeting the Booster reliability goals and are planned to be performed within the scope of normal accelerator maintenance over the next few years. The total cost of these upgrades has been estimated at $1.8M.[3]

Additionally, a greater increase in Booster RF reliability would come with the replacement of older components with solid state devices (in particular, RF driver amplifiers). This is a large-scale upgrade project on the order of $15-20M [4], much of which is periodically being addressed during operation. Strictly speaking this upgrade is not necessary for 15 Hz operation and thus is not included in the costs presented here.

As we shall see, for both the $\mu 2e$ and g-2 experiments beam is to be transferred directly into the Recycler ring from the Booster and out of the Recycler into the P1 transport line. At the moment these functions are performed directly to and from the Main Injector. However, the NOνA project also requires injection into the Recycler from the Booster, and so it will be assumed for our discussion that this functionality has been achieved at the end of that project. Extraction from the Recycler and delivery to the P1 beam line is required for both muon programs, with costs similar to the aforementioned injection system. The difference between g-2 operation and $\mu 2e$ operation could be in the kicker requirements which are addressed separately in future sections.

Particle losses in the Booster are currently observed over a 100 sec running average as detected by the beam loss monitor system and limit the beam delivered by the synchrotron to about 1.6×10^{17} protons/hour. Comparatively, 15 Hz operation at 4 Tp per pulse would produce roughly 2.2×10^{17} protons per hour. It is expected that the new magnetic corrector system, the installation of which will be completed in 2009 under the Proton Plan, will allow for this increased intensity under 15 Hz operation.

In each of the programs described below, the antiproton source storage rings are utilized. These rings were not built with the required proton flux in mind, in particular for the $\mu 2e$ experiment. Thus, measures must be taken to improve the environmental impact of the new uses of these facilities. As these requirements are different for the two programs, each is further addressed in their respective sections of the document.

1.2 Summary of Scope

In the spirit of an executive summary, Table 1 outlines the scope of the work to be performed for implementation of the two experiments at Fermilab. First-pass cost estimates are forthcoming.

Table 1: Scope of accelerator system modifications required of accelerator systems to provide beams to muon experiments at Fermilab

	Accel/BmL	System	note
common			
	Booster	RF	upgrade to 15 Hz operation
	RR	inj line	from MI-8 to RR
	RR	ext line	from RR to P-1 line
g-2			
	Recycler	ext line	extraction kicker
	Recycler	RF	system move from MI, upgrades
	AP0	target station	possible new optics, lens upgrades
	Expt Hall	building	new construction
	Expt Hall	cryo	tie in with Tevatron system
	transf. lines	Rad. Safety	mitigation near new building
	transf. lines	Instr/Controls	possible BPM upgrade
$\mu 2e$			
	Recycler	kicker	extraction kicker (use g-2?), or steering dipole
	ACC	RF	upgraded system
	DEB	RF	upgraded system
	DEB	Slow Extr	septa, correctors, feedback system
	Extr Line		new construction
	Extinct Channel		AC dipole system, collimators
	ACC/DEB	Rad. Safety	upgrade for high intensity
	ACC/DEB	Instr/Controls	possible BPM upgrade

2 Muon $g - 2$ Experiment

The g-2 experiment requires 3.09 GeV/c muons injected into an existing muon storage ring that would be relocated from Brookhaven National Laboratory to Fermilab. The muon storage ring is 7 m in radius, giving a revolution time of 147 ns. To account for the injection kicker, the beam pulses need to have lengths of about 100 ns or less. These pulses should be separated on the scale of about 10 ms for the muons to decay in the ring and data to be recorded prior to the next injection. To obtain as pure a muon beam as possible entering the storage ring, the experiment would like a decay channel corresponding to several pion decay lengths = 7.8 m $\times \gamma$ = 7.8 m $\times$ 3.09/0.14 = 7.8 m $\times$ 22 = 170 m. Present understanding of the pion yield off of an 8 GeV target dictates the desire to deliver a total of 2×10^{20} 8 GeV protons on target to obtain 21$\times$ more statistics for the g-2 experiment and give a 0.1 ppm measurement of the muon anomalous magnetic moment.

2.1 Meeting the Experimental Requirements

To meet the above requirements it is envisioned that six Booster batches every MI cycle can be sent to the experiment for an average rate of $6/20 \times 4$ Tp $\times$ 15/sec = 18 Tp/sec. This yields the required total protons on target in about a single "Snowmass year" (10^7 sec) of running. Each batch of 53 Mhz bunches from the Booster would be sent to the Recycler and coalesced into four bunches for delivery to the experiment. Using existing RF systems, possibly supplemented with like-kind components, the four bunches can be formed to meet the demands of the g-2 ring. The re-bunching process takes approximately 30 ms, and the four bunches would then be delivered to the experiment one at a time spaced by 12 ms. Thus, the last bunch is extracted just within the 66.7 ms Booster cycle. The remaining two Booster cycles, before and after this process, allow for pre-pulsing of fast devices prior to the change between NuMI and "muon" cycles. (If this is deemed unnecessary, then eight rather than six Booster cycles could feed the experiment during each MI cycle.) Figure 1 shows the proposed time line of events during MI operation.

Once extracted from the Recycler a bunch is sent toward the existing, though possibly modified, antiproton target station for $\sim$3.09 GeV/c pion production. A "boomerang" approach utilizing the Debuncher and Accumulator rings can be used as a delay line allowing for pion to muon decay, assuming a final location of the g-2 ring in the vicinity of the production target. A schematic of the beam line system is presented in Figure 2. The total length of the decay line would be $\sim$900 m. To obtain even further purity of the muon beam, multiple revolutions in the Debuncher or Accumulator rings could be considered, perhaps as an upgrade to the program. This upgrade would require the development of an appropriate kicker system and is not included in this first design iteration. The 900 m decay length, however, is already a large improvement over the original layout at BNL.

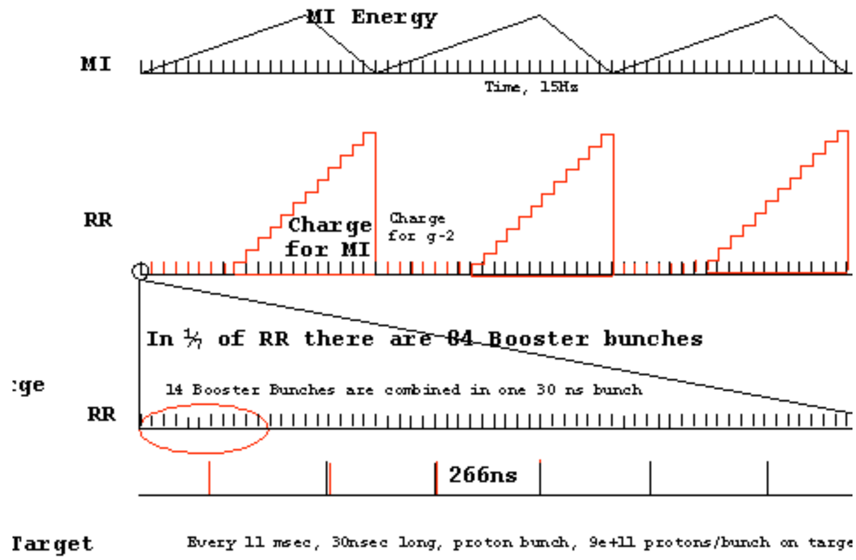


Figure 1: Timing diagram for the proposed g-2 operation.

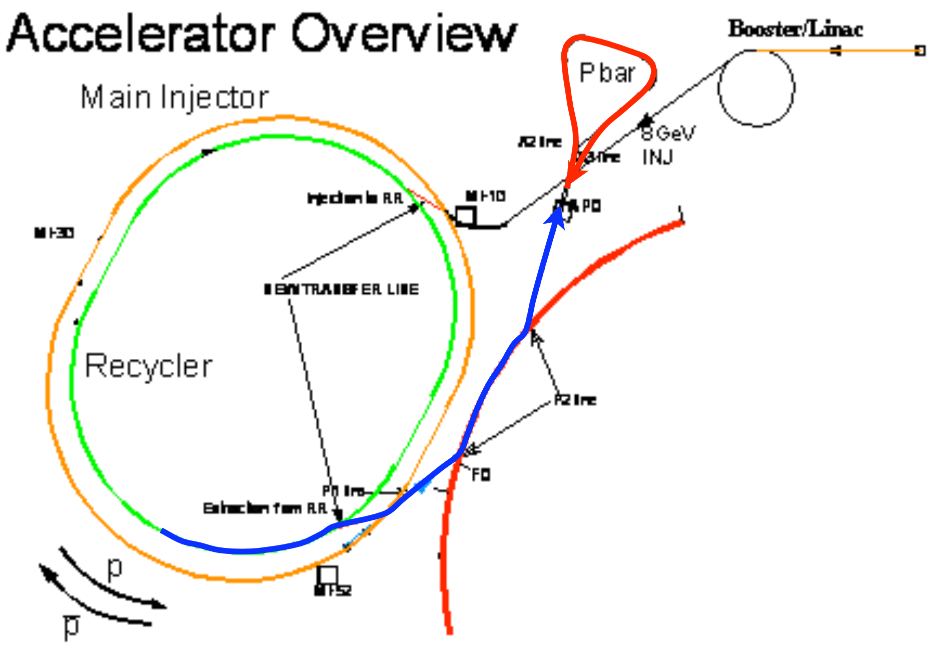


Figure 2: Beam transport scheme for g-2 operation. Beam is prepared in the Recycler, exits via the P1 line, passes through the Tevatron tunnel into the AP1 beam line, and to the AP0 target area. (Blue curve.) Pions, decaying to muons, are transported from the target through the AP2 line, once around the "pbar" rings (Debuncher/Accumulator) and back toward the experimental hall near AP0 via the AP3 beam line. (Thick red curve.)

2.2 Beam Preparation

The major proton beam preparation will be performed in the Recycler ring. A broadband RF system like that already installed in the Recycler would be used, except twice the voltage may be required. The 2.5 MHz (max. $V_{rf} = 60$ kV) and 5 MHz (max. $V_{rf} = 15$ kV) RF systems that presently reside in the MI would be relocated to the Recycler. Upgrades to increase their maximum voltages by roughly 10-30% may be required. All of these upgrades are assumed for the cost estimate.

As described in [5], the bunching scheme is to use a four period sawtooth wave form across the Booster batch produced by the broadband RF system to break the batch into four segments and rotate them in phase space sufficiently that they can be captured cleanly in a linearized bucket provided by the resonant RF. Each of the four resulting bunches is $\sim$100 ns long. The first bunch is extracted immediately and the latter three are extracted sequentially at half periods of the synchrotron oscillation. The beam loading of the resonant cavities will be considerable, and further details need to be considered. It is plausible to expect that a feedforward system can be developed without serious difculty. A combination of feedback with feed forward is potentially better yet, but feedforward will be required with or without feedback. Figure 3 shows the resulting beam structure in the Recycler if the beam were not extracted. The plan would be to extract one pulse at a time, every 12 msec, when the bunches are at their narrowest time extent

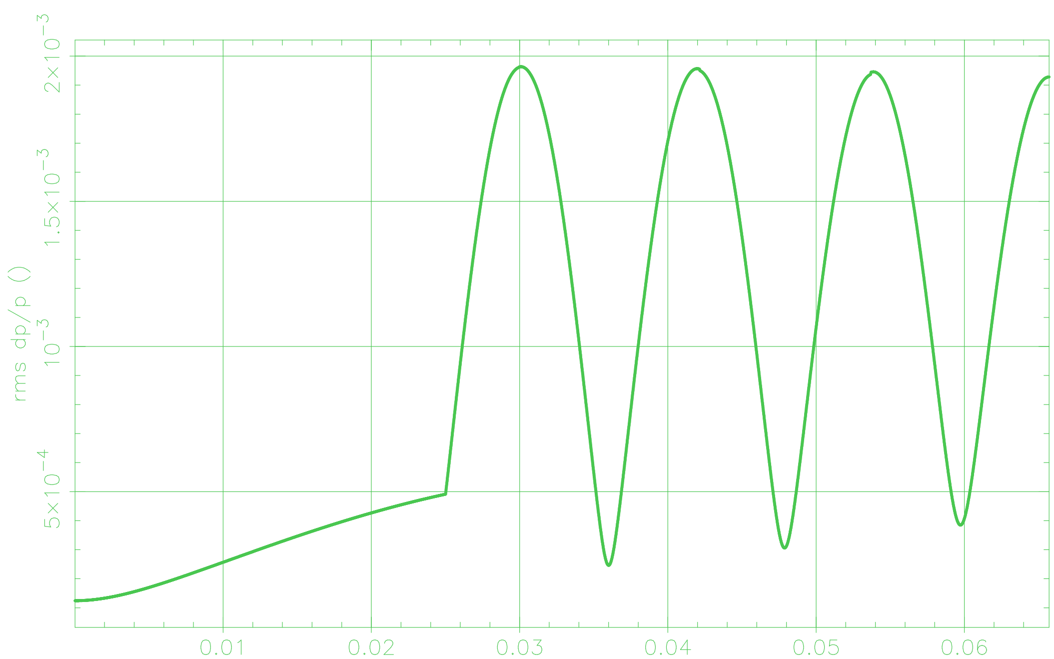


Figure 3: Resulting relative momentum spread ($\Delta p/p$) *vs.* time in seconds following injection into the Recycler. After an initial phase using the broadband RF system, beam is captured into four buckes. The beam rotates within the four buckets with period 12 msec and is extracted one-by-one as the momentum spread reaches its peak (pulse length is at its shortest).

(4σ widths of 38-58 nsec). The four bunches would be separated by roughly 400 nsec center-to-center. For the sequence shown, the RF systems require voltages of 4 kV (broadband), 80 kV (2.5 MHz), and 16 kV (5.0 MHz). A longitudinal emittance of 0.07 eV-sec per 53 MHz Booster bunch was assumed.

2.3 Beam Delivery and Transfer

Following the beam trajectory starting with extraction from the Booster, we see that the proton beam needs to be injected into the Recycler from the MI-8 beam line at the MI-10 region of the Main Injector tunnel. This maneuver will be facilitated through the NOνA project, which requires the same injection procedure. Once prepared with the RF systems as described above, the beam will need to be extracted from the Recycler and injected into the P1 beam line. The extraction location is at the MI-52 tunnel location, where the Main Injector ties into this same beam line. (See Figure 2.) The P1 beam line is used to deliver 8 GeV antiprotons from the Accumulator into the Main Injector (and on into the Recycler) in the reverse direction. During the g-2 operation, however, the Main Injector will contain beam destined for NuMI and so this region will need to be modified in almost exactly the same way as MI-10 to transport protons directly into the P1 line from the Recycler.

An appropriate kicker system will also be required for this region to extract one-by-one the four proton bunches from the Recycler. The four bunches will be separated by approximately 200 nsec, so the kicker must rise in $\sim$180 nsec, say, and have a flat top of $\sim$50 nsec. Remember that the Recycler has a circumference seven times that of the Booster, and only one Booster batch will be injected at a time. Thus, the last proton bunch of the four will be separated from the first by about 8.6 μsec or more. The kicker can then have a fall time on the order of 5 μsec, say, and must be pulsed 4 times separated by 10 msec within a Booster cycle. This operation is repeated 6 times every 1.33 sec MI cycle.

From the entrance of the P1 line through the Tevatron injection Lambertson (which is kept off during this operation) the beam is directed through the P2 line (physically located in the Tevatron tunnel) and into the AP1 line toward the AP0 target hall. Again, since this system is run at 8 GeV for antiproton operations, no modifications are required for beam transport in g-2 operations. After targeting, which is discussed in the next subsection, 3.09 GeV/c pions are collected into the AP2 line which is "retuned" to operate at 3.09 GeV/c rather than today's 8.89 GeV/c antiproton operation.

To obtain a long decay channel for the pions off the target, the beam is transported through the AP2 line, into the Debuncher ring, immediately transfered into the Accumulator ring and out again into the AP3 line, directed back toward AP0. (See Figure 2 again.) As this will be the only use of these rings, kicker magnets will not be required in this configuration, and the rings will be "partially powered" using only those magnet strings required to perform the "boomerang". Either corrector magnets or DC powered trim magnets will be used in place of kickers to perform the injection/extraction between the partially powered rings and associated beam lines. It is currently envisioned that the g-2 ring will be located on the surface near the AP0 service building as indicated in Figure 4. The AP3 beam line will be modified to

Figure 4: Proposed location of the new g-2 experimental hall (yellow).

"punch through" the ceiling of the tunnel enclosure and up into the g-2 ring. The tie-in to the experimental facility will be discussed below in a subsequent subsection.

As can be seen, little modifications are required of existing beam lines to perform the beam transport all the way from the Booster to the g-2 ring. The end of the line and connection to the experimental ring requires design, but should be straightforward. It should also be pointed out that the Debuncher, Accumulator, and Recycler rings all have much equipment installed to perform stochastic cooling (and, in the Recycler, electron cooling) which can and should be removed to generate less aperture restrictions for the high intensity operations of any 8 GeV experimental program.

2.4 Target Station

Various options are being explored at this time for meeting the targeting requirements of the experiment, and this remains as a major R&D area for the proposal from the point of view of the accelerator complex. The most straightforward approach would seem to be using the existing AP0 target more-or-less "as is." The present system is used for selecting 8.9 GeV/c antiprotons from a 120 GeV/c primary proton beam. For g-2 one would select $\sim$ 3.09 GeV/c pions from 8.9 GeV/c primary protons by re-tuning the beam lines upstream and downstream of the target. The major issue with this particular scenario is the Lithium lens used for antiproton production. Options for re-configuring the lens and its power supply into a useful operational mode, such as to pulse every 12 msec or to generate a single pulse with a flat top of about 40 msec, with an appropriate reduced current, are being investigated. If these prove infeasible or

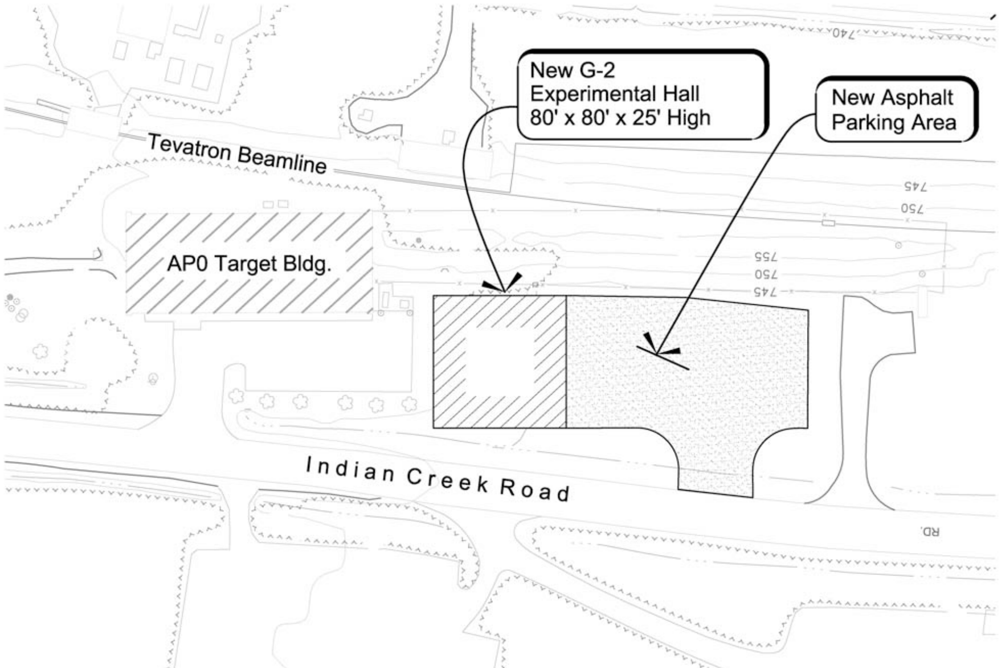


Figure 5: Location plan of the new g-2 experimental hall.

prohibitive, then other optical solutions will need to be considered, such as a quadrupole triplet system in place of the Lithium lens. The AP0 target vault and surrounding area is a very difficult place in which to work, and redesign of the area could be expensive. Investigations of the target station design are on-going.

2.5 Experimental Facility

A first pass look at an experimental building was performed at Fermilab.[6] The building would be approximately 80 ft × 80 ft and includes a full-span 40 ton bridge crane. Other details of the cost exercise may be found in [6]. The building is large enough to enclose the g-2 ring as well as associated electronics and counting room. A schematic of the building location and adjacent parking area are found in Figure 5.

The cryogenic needs of the experiment can be met by the Tevatron accelerator cryogenics system with some modifications and additional transfer line work. The Tevatron is located only about 50 ft away from the AP0 service building, and is expected to be in 80°K standby mode during the time span of the experiment. Additionally, it is assumed that the Tevatron F2 magnet string is allowed to be warmed up to room temperature during this time, freeing up the refrigeration system at F2 to be used for g-2. A cost estimate of the required modifications has been performed and documented.[7]

The exact location of the building south of AP0 will be determined by the final design of its connection with the beam transport line. The beam line will need to emerge vertically from the tunnel containing the AP3 line and make a roughly 90° horizontal bend into the experiment building.

2.6 Environmental Assessment

As noted previously, the average particle delivery rate to the g-2 target would be 18 Tp/sec. At 8 GeV kinetic energy per proton, this translates to approximately 27 kW beam power onto the target station. Present day antiproton production operation utilizes two Booster batches of 4 Tp every 2.2 sec at a particle energy of 120 GeV, which corresponds to approximately 67 kW beam power onto target. Thus, the activation of the target hall and beam lines leading up to it is expected to be well below present day levels. This should also be expected of the beam delivery from the target into and out of the Debuncher/Accumulator rings and back to the AP0 region through the existing beam lines since this will be performed as a single-pass beam transport using DC magnetic elements. The final design of the connecting region between the AP3 beam line and a new g-2 experimental hall will need to be assessed for appropriate shielding. While further work will be needed to validate the environmental impact of the new use of these facilities for g-2, as well as for the experimental building itself, this is seen as a straightforward effort.

2.7 Accelerator R&D

As of this writing the following items need to be addressed:

- *Targeting and Pion Flux*: The target optics needs to be verified and/or re-designed, including the possible use of the (modified) lithium lens, and the target material chosen or verified. The expected pion flux from targeting of 8 GeV kinetic energy protons and the associated production acceptance into the transport line need to be carefully examined, modeled, and documented.

- *Intensity Limitations*: Studies should be performed on the intensity limitations of the Recycler, for example the impedances expected to be present during g-2 operation. While many of today's electron and stochastic beam cooling components can be removed, the addition of new RF systems will create new sources of impedance that need to be examined. The NOνA program, for instance, is expecting a low impedance system to meet its intensity requirements, and any modifications must be consistent with this expectation.

- *Bunch Formation*: Optimization of the bunch formation in the Recycler and final definition and specification of the RF requirements need to be completed.

- *Final Transport*: The final stage of beam transport from the AP3 beam line up and into the g-2 ring in the experimental hall needs to be designed and properly costed.

3 Muon to Electron Conversion Experiment

The $\mu 2e$ experiment is designed around a total delivery of 4×10^{20} protons on target, to be collected during one or two years of running. As outlined in their Letter of Intent[8], the experiment wishes to inject muons onto an aluminum stopping target in narrow (<200 nsec) time bursts, separated by intervals of about 1.5 μsec, somewhat larger than the lifetime of muonic aluminum. Muon to electron conversion data would be taken between bursts, after waiting a sufficient time ($\sim$700 ns) for the prompt background to subside. A suppression (extinction) of the primary proton beam between bursts by a factor of 10^9 relative to the burst itself is necessary to control the prompt background.

3.1 Meeting the Experimental Requirements

The proton delivery method proposed in the LOI is to send Booster beam through the Recycler and directly inject into the Accumulator, where several Booster batches would be momentum stacked. Thus, in this scenario, the Recycler is used as a simple beam transport, and the Accumulator/Debuncher rings are used to generate the desired beam properties. Since this is carried out with 8 GeV kinetic energy proton beams, no new beam lines are required, and all magnetic elements operate at their present-day field strengths. A schematic of the beam line system is presented in Figure 6.

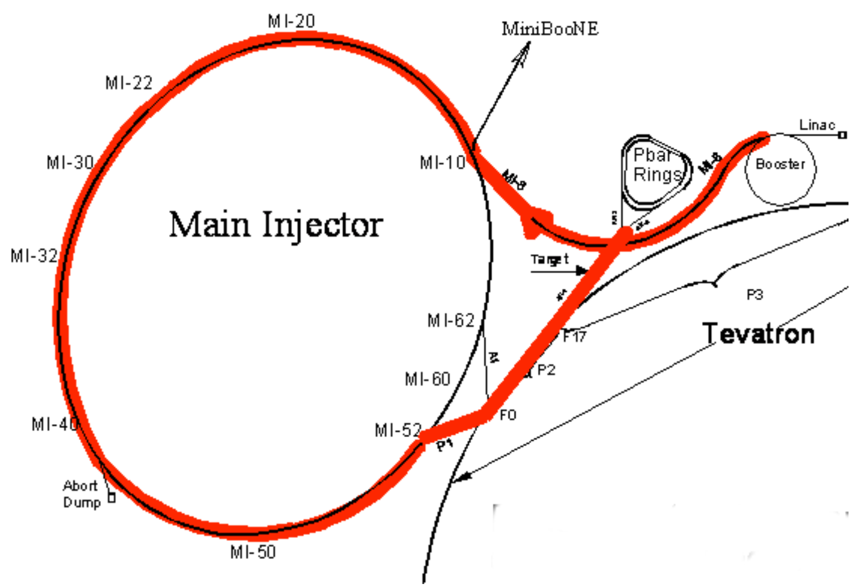


Figure 6: Beam transport scheme for $\mu 2e$ operation.

As in the g-2 operation, six of the eight free Booster cycles are used to feed 4 Tp per pulse to the $\mu 2e$ experiment, three batches at at time in this case. Figure 7 shows the proposed time line of events during MI operation. Three consecutive batches are momentum stacked into the Accumulator ring and then coalesced into a single bunch using an $h = 1$ RF system. This beam is then transferred into the

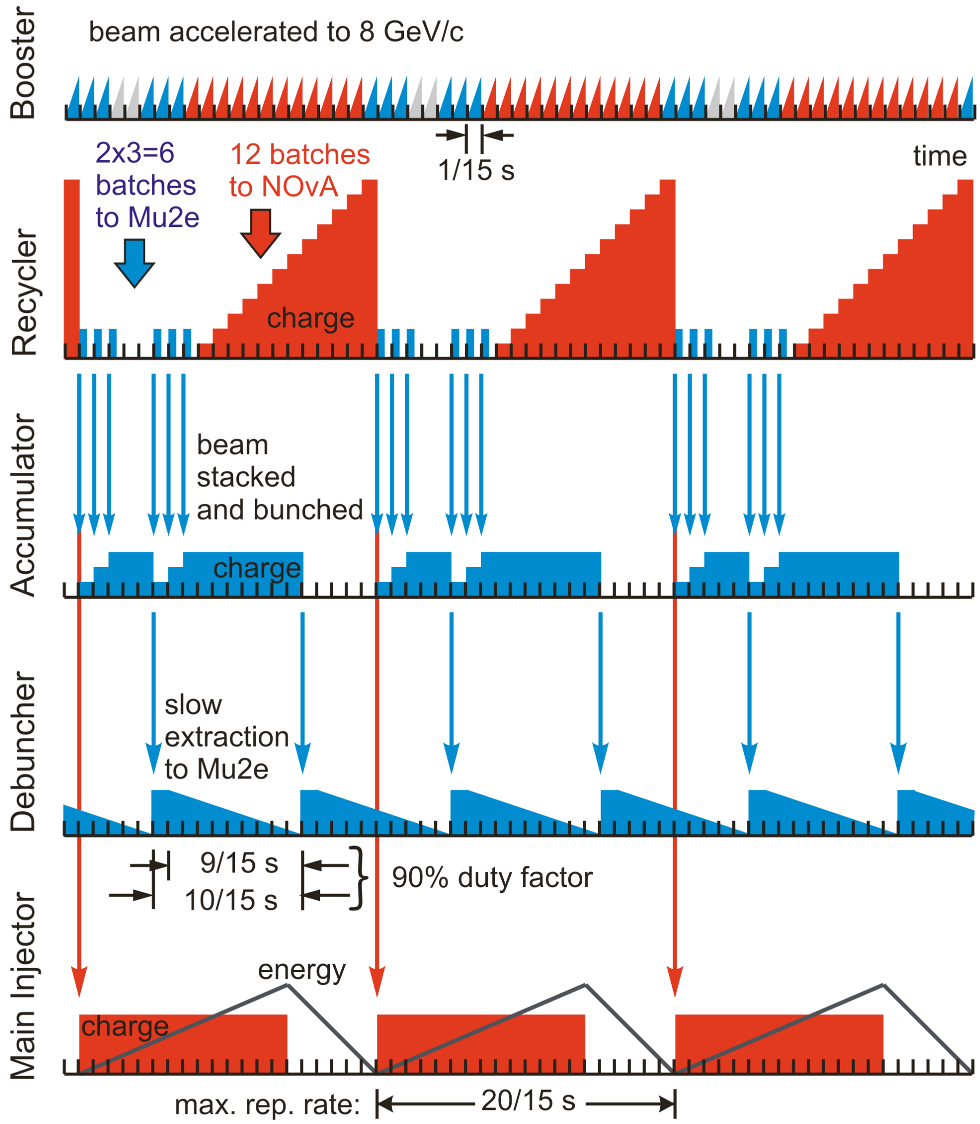


Figure 7: Timing diagram for the proposed $\mu 2e$ operation.

Debuncher ring where a bunch rotation is performed and a single short bunch, of $\sim$40 nsec extent (rms), is captured into an $h = 4$ RF system. The total process to this point would occur within five Booster cycles. The beam then would be resonantly extracted from the Debuncher over the next 9 Booster cycles. This single bunch would produce a train of 40 nsec (rms) bursts being emitted from the Debuncher at 1.7 μsec intervals (the revolution period of the Debuncher ring) producing a structure well suited to the $\mu 2e$ experiment. Beam would be transported through an 8 GeV beam line to the experiment, presumably located to the west of the Debuncher/Accumulator tunnel. During this extraction from the Debuncher, the Accumulator can be re-filled with three more Booster batches to await transfer to the Debuncher. As can be seen in Figure 7, a total of six batches per Main Injector cycle time of 1.33 sec can be slow spilled to the experiment with a duty factor of 90%. If each batch contains 4 Tp, then the Debuncher will start with 12 Tp and if spilled over 9/15 sec at 1.7 μsec per burst will yield 3.4×10^7 protons per burst onto the target, with an average spill rate of 18 Tp/sec and a total of 1.8×10^{20} protons on target within a "Snowmass year".

An important specification for this beam will be the extinction factor, or suppression of out-of-bucket beam, as this is a limiting background for the experiment. This is discussed further in a separate subsection below.

3.2 Beam Delivery and Transfer

As presented for the g-2 experiment, 8 GeV proton beam must be injected from the MI-8 transport line into the Recycler, and extracted from the Recycler into the P1 transport line. The injection line, as stated previously, is intended to be part of the NOνA project. While g-2 requires a fast kicker to extract one bunch at a time, the $\mu 2e$ experimental scenario described above only requires beam to circulate part-way around the Recycler. Thus, either (a) the same – perhaps slightly-modified – extraction kicker used for g-2 can be used to extract for $\mu 2e$, or (b) a "switched" dipole magnet can be turned on during the Booster cycles from which beam passes through the Recycler.

Once out of the Recycler and into the P1 line, the beam is transported to the Accumulator ring in the same manner as is done presently for so-called "reverse proton" operation. Naturally, hardware to transfer beam between the Accumulator and the Debuncher also exist and are used routinely.

The beam line connecting the Debuncher ring with the experiment will be of new construction. Currently, a site west of the Debuncher ring as depicted in Figure 8 is being examined. While a design for the beam line elements is not in place, it should be conceptually similar to other 8 GeV transport systems, for example the miniBooNE beam line. The exceptional aspect of this design will be the extinction channel, which is described separately below. Additionally, extraction septa – electrostatic and magnetic – will be necessary as well as appropriate magnetic elements to be used for resonance control in the slow extraction process. Again, this is discussed in a separate subsection.

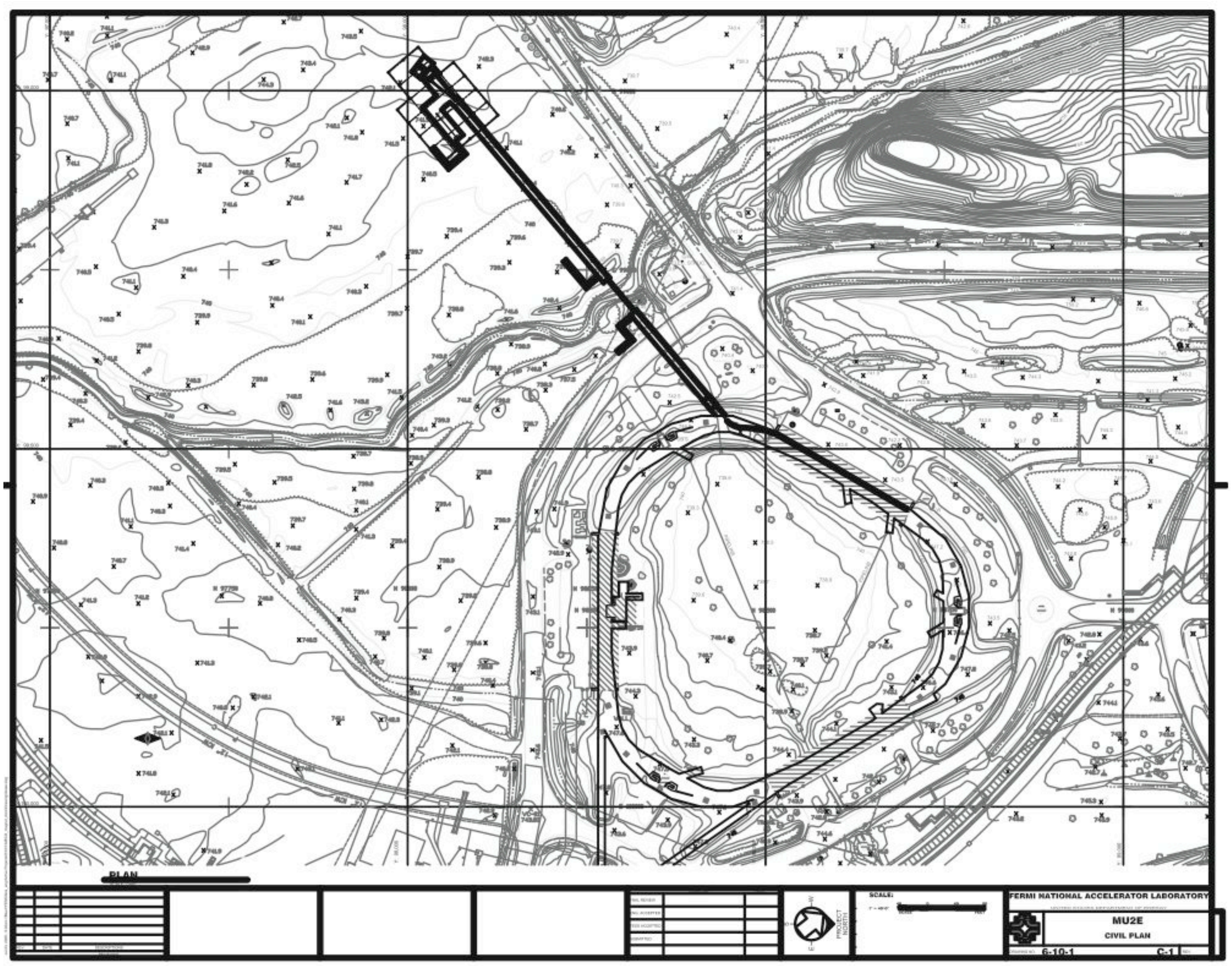
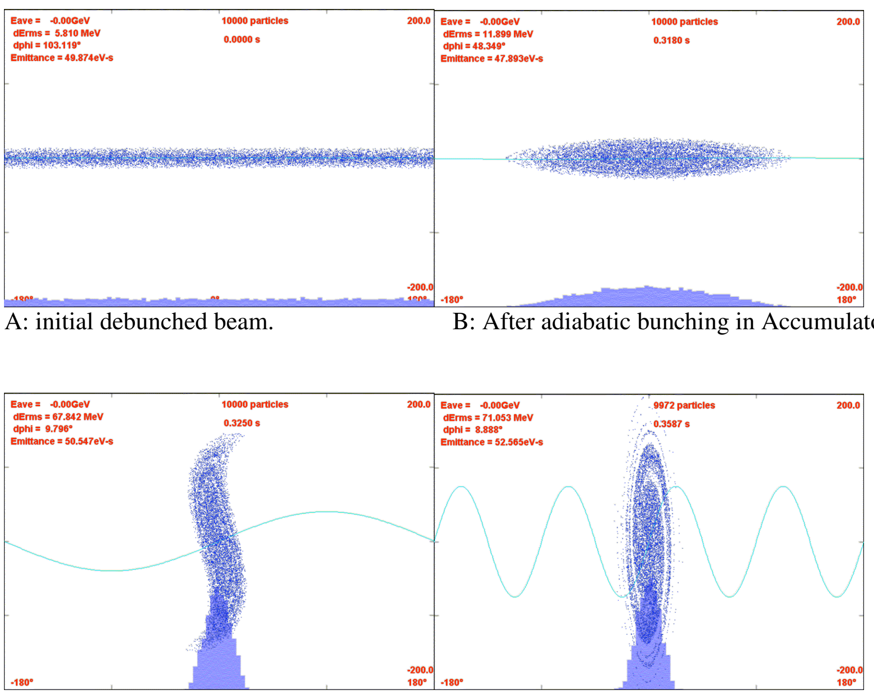


Figure 8: Proposed site of the $\mu 2e$ experimental area and adjoining beam transport line.

3.3 Beam Preparation

As noted earlier, the major beam preparation for the $\mu 2e$ experiment is performed in the Accumulator and Debuncher rings. The Accumulator with its large aperture and momentum stacking systems is well suited for accumulating pulses of protons from the Booster (*via* the Recycler) and stacked three at a time. Protons enter the Accumulator onto an "outer" orbit, are captured with 53 MHz RF and decelerated toward the "core" orbit where they merge with already circulating particles. Should the present system require more total voltage to enable three consecutive batches from the Booster to be accumulated, the Debuncher's 53 MHz system, not needed in the new scenario, can be relocated to the Accumulator. Once three Booster batches have been accumulated in this way, the present scheme ([9]) uses an $h = 1$ RF system that is turned on adiabatically to 4 kV, capturing the beam into a single bunch. This allows enough time for an extraction kicker to fire sending the beam to the Debuncher ring. Once in the Debuncher, a similar $h = 1$ system running at 40 kV will cause the bunch to rotate in phase space, generating larger momentum spread but shorter bunch length. After $\sim$7 msec the bunch rotates 90° at which time it is captured by an $h = 4$ RF system running at 250 kV. This system keeps the beam bunched with an rms length of 38 nsec and energy spread of $\pm$200 MeV. Figure 9 displays the evolution of the longitudinal phase space through the process.



A: initial debunched beam. B: After adiabatic bunching in Accumulator.

C: After ϕ-E rotation in Debuncher D: After h=4 bunching in Debuncher.

Figure 9: Bunched beam preparation for the $\mu 2e$ experiment. The dots are particle distributions in phase (horizontal, $\pm$ 180° or $\sim$ $\pm$0.85 μsec) and energy (vertical, $\pm$200 MeV) phase space, with histograms shown along the bottom edge. Curves indicate the RF wave forms used.

The Accumulator and Debuncher rings at present contain $h = 1$ and $h = 4$ RF systems, but are run at much lower voltages (< 2 kV). Thus, upgrades to these systems will be in order, including additional cavity hardware and high level RF amplifiers.

3.4 Slow Extraction from Debuncher

Resonant extraction is a technique for slowly and relatively evenly removing particles from a synchrotron, and has a long history at Fermilab. The original Main Ring, the Tevatron, and the Main Injector have all used, or are using, half-integer resonant extraction for producing slow spill particle beams for targeting. In these cases, the non-integral part of the betatron tune resides near one half, and a fast quadrupole magnet system with feedback circuitry is used to carefully ease the tune toward the half-integer. Due to nonlinear magnetic fields inherent in any real magnet system, which can be further enhanced by the introduction of tunable octupole magnets, particles with larger betatron oscillation amplitudes will have tunes that go on-resonance first, increasing their amplitudes even further, and these particles can be directed into an extraction channel leaving the synchrotron. As the tune slowly approaches 0.5, the higher amplitude particles are "peeled off" from the distribution, generating a smooth stream of particles leaving the ring.

The Debuncher, with its three-fold symmetry and a design tune near a third of an integer, makes the use of third-integer extraction a possibly attractive option for the $\mu 2e$ application. Here, sextupole magnets are used to enhance the resonance at a tune of 1/3 generating a dynamic aperture (or stable phase space area) that is proportional to the difference of the tune from 1/3. As the tune adiabatically approaches 1/3, particles that suddently find themselves outside the dynamic aperture stream away from unstable fixed points in a well defined pattern and, as in the half-integer case, will eventually wander to the other side of a septum to be directed out of the synchrotron.

The exact system to be chosen will require further study. One of the major benefits of half-integer extraction is the fact that the entire phase space can be made unstable when the tune gets close enough to 0.5 (when the beam enters the half-integer stop-band gap). This allows for the complete removal of the particles from the synchrotron to the experiment, and is one of the primary reasons half-integer extraction was chosen for the three Fermilab synchrotrons mentioned above. The third-integer system will have particles remaining in the ring which will need to be aborted at the end of the slow spill. Also, when the particle beam has a large momentum spread, which will be true for either case with the Debuncher application (± 200 MeV/ 8.9 GeV = $\pm 2\%$), the chromaticity will need to be very finely controlled in coordination with other extraction parameters.

Of course third-integer extraction is routinely performed at other synchrotrons; for example, the AGS at Brookhaven National Laboratory ran in this mode for many decades, with large momentum spread in its latter years of running high intensity. The exact mode and details of the operation will be worked out over the next several months. The large aperture of the Debuncher should help in the efficiency of the extraction system, as the inefficiency is governed by the ratio of septum thickness to the step size of the

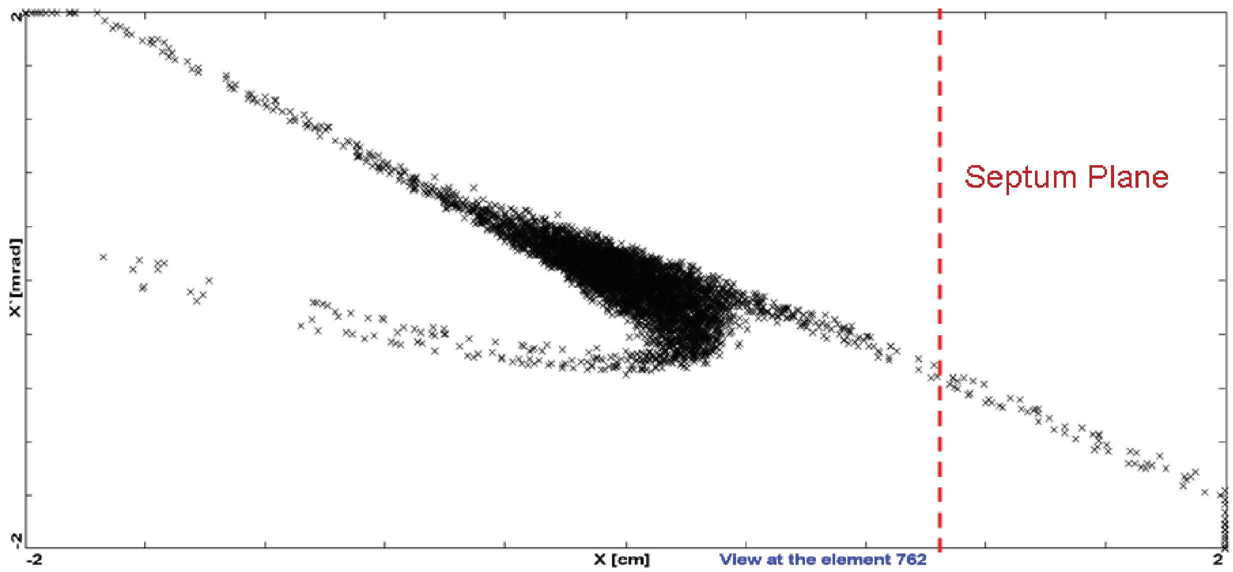


Figure 10: Result of preliminary simulation of third-integer extraction from the Debuncher, showing particle distribution in horizontal phase space. The position of the electrostatic extraction septum is indicated to the right. The effects of the momentum distribution are not shown.

nonlinear amplitude growth; with a large aperture, one can make the step size larger and gain in efficiency.

In either case, the required components are clear. One needs an electrostatic septum, a magnetic septum, and a set of fast (likely air-core) corrector magnets (quadrupoles or sextupoles, depending on the choice of resonant tune). A preliminary look at third-integer extraction was performed using the Debuncher lattice and appropriate septa.[10] Using a 3 m long version of the Main Injector electrostatic septum (80 kV across a 1 cm gap) a 2.5 cm transverse deflection can be generated at the magnetic septum location, 90° downstream in betatron phase. A magnetic field of 0.8 T is enough to clear the downstream quadrupole using a 1 m version of a Main Injector Lambertson magnet followed by a 2 m C-magnet. The resonance-driving sextupoles were located in the straight sections of the Debuncher lattice for this simulation. A small set of corrector magnets (on the scale of 4-8) will be sufficient, with an associated feedback circuit on their power supply system. The resulting phase space from the calculation is shown in Figure 10. While these first results are encouraging, the simulation did not take into account the large momentum distribution nor chromatic effects of the resonance sextupoles (or resonant effects of the chromaticity sextupoles), *etc.* Full simulations of the process using more realistic beam and synchrotron parameterizations can be contemplated, as the entire slow spill will occur in only $(9/15)\ /\ (1.7 \times 10^{-6}) =$ 350,000 revolutions. One should also be reminded that resonant extraction is an inherently lossy process, the case above leading to an inefficiency of roughly 2% or slightly higher.

3.5 Extraction Line

A design for the extraction line leading toward the experiment is just being started. The length of the extraction line, using the layout depicted in Figure 8, will be approximately 200-240 m and its cost and complexity roughly can be scaled from the many other 8 GeV beam lines built at Fermilab over the past decades. One exceptional feature of the line is the Extinction Channel, which is presented in further detail below. Otherwise the line will contain on the scale of 20 quadrupoles, a few minor bend centers, and standard cooling, powering, and instrumentation requirements. The beam line will be part of the formal $\mu 2e$ project and hence the costs associated with it would be charged to the project accordingly. The estimate provided at the end of this document is a first-pass consideration for early costing purposes and will be updated through future efforts.

3.6 Extinction Channel

To meet the requirement that no particles reach the detector from the direction of the primary proton beam between beam bursts to the level of 10^{-9}, a beam extinction channel is proposed for the downstream end of the extracted beam line. This portion of the transport system will utilize a set of rapid cycling dipole magnets (AC dipoles) on either side of a focusing channel the middle of which contains collimators. The dipole magnets cycle at half the burst frequency ($\sim$300 kHz) and kick the unwanted beam well into the collimator iron. The concept is shown schematically in Figure 11. Further details of the concept may

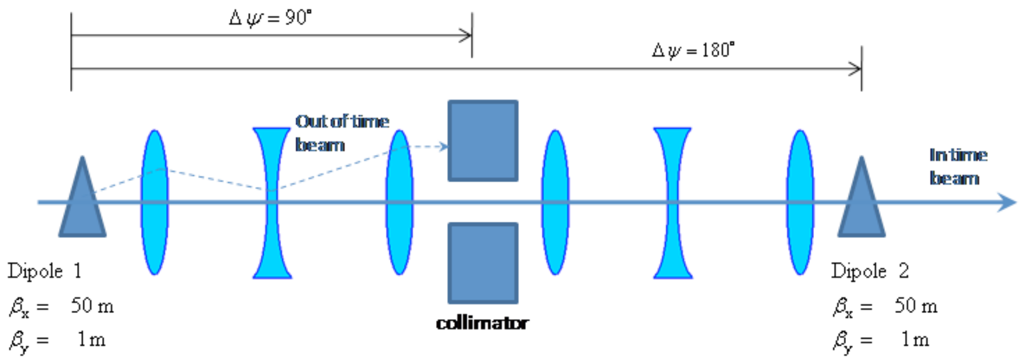


Figure 11: Schematic of extinction channel. Two AC dipoles steer the trajectory into collimators at an oscillation frequency of 300 kHz.

be found in [11] and a conceptual design of the magnet system is found in [12]. Thus, for costing purposes, the focusing elements of the extinction channel should be considered to be part of the extraction beam line, and the additional components required would be the two AC dipoles, including their power supply, the collimation system, and the extra instrumentation required for measuring and monitoring the level of particle extinction.

3.7 Experimental Facility

The complete experimental facility, at present proposed to reside just to the west of the antiproton source, will be part of the $\mu 2e$ project and is not considered here to be part of the accelerator complex requirements. The facility will include the target for the experiment, decay channel and detector, and associated equipment and utilities.

3.8 Environmental Assessment

As was stated up front, the antiproton source enclosure was not designed to handle the proposed particle rates expected for the $\mu 2e$ experiment. While there is a finite beam lifetime in a synchrotron, due to diffusion of the particle trajectories from beam-gas scattering for example, the predominant beam loss mechanisms are often associated with fast losses during the injection and extraction processes. Suppose that a fraction f of the particles delivered are lost during their stay. A typical value might be f = 1-5%. And, assume that this fraction will be similar in both the antiproton and the $\mu 2e$ operations.

The present antiproton operation accumulates approximately 25×10^{10} antiprotons every hour. In the $\mu 2e$ experiment, the particle flux is expected to be on the order of 2×10^{13}/sec. Thus, the particle loss rate might be (20 Tp/sec)/(0.25 Tp/3600 sec) = 300,000 times larger for $\mu 2e$ operation than present day levels.

Table 2: Particle loss rates, assuming f=0.01 (for scaling purposes; see text).

	pbar	$\mu 2e$
particles injected	70×10^6/sec	20 Tp/sec
particles lost	700×10^3/sec	0.2 Tp/sec
ave. power loss	0.001 W	286 W
	2×10^{-6} W/m	0.6 W/m

Table 2 compares the loss rates for the two operational scenarios. The average power loss per meter assumes a uniform loss over the circumference (R = 75 m). Since losses tend to be localized, undoubtedly extra shielding in the tunnel would be implemented at the injection/extraction locations, for instance, and losses along the arcs of the ring would be less that quoted here. However, the Accumulator/Debuncher tunnel and earth berm were not built to handle this loss rate and measures must be taken to mitigate radiation concerns. For comparison, the Booster operates routinely at a beam loss rate of approximately 500 W, or $\sim$1 W/m when averaged over the ring. Losses that occur around the circumference in uncontrolled regions are typically 300 W, or 0.6 W/m. Thus, shielding and protective measures at the level of that of the Booster will be required for these rings and service buildings.

Additionally, the Debuncher beam is to be resonantly extracted which is in itself an inherently lossy process (to the 1-5% level). However, these losses are clearly localized and activation concerns can be mitigated with appropriate local shielding in the tunnel.

Finally, the extinction channel region will need to be considered for its residual activation. The concept is for the AC dipoles to clean out particles that find themselves outside of the preferred $h = 4$ bucket formed in the ring; thus, the rates should be very low during ideal operation. However, during commissioning and tuning it may be possible for much higher intensities to reach the collimators and this area will need to be protected accordingly.

All of these issues will require substantial consideration, design and optimization. While straightforward and well understood mitigation methods exist, the cost estimate for $\mu 2e$ will need to include the work necessary for addressing these inherent beam loss issues.

3.9 Accelerator R&D

As of this writing the following items for $\mu 2e$ need to be addressed:

- *Momentum Stacking*: The voltage requirements for the momentum stacking system needs to be finalized, including estimates of potential beam loading.

- *Intensity Limitations*: Estimates need to be performed on the foreseen limitations on intensity in the Accumulator and Debuncher rings when reconfigured for $\mu 2e$ operation. Many small aperture and large impedance devices can be removed from the stochastic cooling systems, but new RF cavities with higher-than-present voltages, operating with higher-than-present beam currents will be installed. The Accumulator will run at 2-3 times its highest intensity to date, though not stored for hours as at present. The beam will be stored in the Debuncher for approximately 667 msec compared to the typical $\sim$2100 msec of present operation, but will contain about 40,000 times more particles than during antiproton production. A beam abort system will also need to be designed. Operational scenarios will dictate whether this system and its associated beam dump should be inside the Debuncher tunnel or within the extraction beam line. Space charge effects, especially in the Debuncher, will be formidable in this baseline configuration especially due to the large bunching factor associated with producing 12 Tp within a 40 nsec bunch, and will need to be addressed.

- *Bunch Formation*: Further optimization of the bunch formation process should be considered.

- *Resonant Extraction*: A more developed plan for resonant extraction and its modeling, including the effects of beam momentum spread, potentially high space charge tune spread, and realistic apertures, is required. Shielding around the extraction septum area to locally maintain losses of 2-5% needs to be designed. The extraction inefficiency needs to be better estimated. The requirements and expectations for the slow spill feedback circuit need to be developed.

- *Extraction Line*: A full design of the extracted beam line is required, including appropriate matching into and out of the extinction channel and adequate resolution of physical constraints between the ring and experimental hall.
- *Extinction Channel*: The extinction channel needs to be taken from conceptual layout to an engineering design, along with appropriate specifications for the required instrumentation for measuring and monitoring the level of achieved extinction.
- *Radiation Safety*: A careful analysis of the necessary safe guards for running high intensity beams in the antiproton enclosures needs to be performed. Beam loss rates several orders of magnitude greater than present are expected to be encountered. Passive, active, and perhaps electronic safety measures will need to be designed and costed.
- *Instrumentation*: At present the antiproton rings primarily contain debunched beam whereas the $\mu 2e$ experiment will form bunched beam in both the Accumulator and Debuncher rings. An analysis of the present instrumentation and possible modifications or upgrades necessary to monitor bunched beam will need to be performed.

4 Integration

In common with both experiments being considered are the requirement for the Booster synchrotron to operate at its maximum rate of 15 Hz, and for transfers into the Recycler from the MI-8 beam line and out of the Recycler into the P1 beam line to occur. For $\mu 2e$ these transfers can be performed using pulsed magnets as the Recycler is to be used as a beam transport line. However, for g-2 operation kicker magnets would be required as beam will circulate within the Recycler. With this in mind, and as the g-2 experiment could conceivably come on line prior to $\mu 2e$, the same set of kicker magnets could in principle be used for both. The use of common kickers could also allow for the two experiments to be run "simultaneously," on alternating MI cycles for instance, or in some similar variation.

One should also consider the impact on other foreseen programs using the present complex. The scenarios described within this report have no impact on the operation of NuMI/NOνA by design. Another program on the horizon is microBooNE, which uses 8 GeV protons from the Booster as well. This experiment requires beam from the Booster through the MI-8 beam line and into the existing miniBooNE beam line, which is implemented through a switching magnet in the MI-8 line. If the program dictates that miniBooNE operates during the same time period as g-2 and/or $\mu 2e$ then the appropriate switching capability will need to be examined and designed in.

The set of parameters provided below assumes six of the eight unused Booster cycles during a Main Injector ramp are used for one of the experiments, and that the output of the Booster is 4 Tp per pulse, both conservative estimates.

While several R&D studies need to be performed as listed above, many of the costs of the required systems can be readily estimated. The type and approximate amount of hardware can be inferred, though the exact parameters will need to be further refined. A first-order cost estimate is in preparation and will be provided in future versions of this document.

4.1 Parameter List

Table 3: Parameter lists for proposed muon experiments at Fermilab.

	g-2	$\mu 2e$	
p momentum on target	8.89	8.89	GeV/c
Booster Rep. Rate	15	15	Hz
MI cycle	20	20	1/(15 Hz)
Pulses per MI cycle	6	6	
p per Booster cycle	4	4	Tp (10^{12} particles)
$\langle p/\text{sec}\rangle$ to target	18	18	Tp
$\langle p/10^7\text{sec}\rangle$ to target	1.8	1.8	10^{20}
$\langle$pulses/sec$\rangle$ to target	4.5	529,400	Hz
duty factor	30	90	%
Maximum stored in Recycler	4		Tp
Maximum stored in Accum/Deb		12	Tp
Recycler RF			
broadband	4		kV
2.5 MHz	80		kV
5.0 MHz	16		kV
Accumulator RF			
$h = 84$ (53 MHz)		50	kV
$h = 1$ (625 kHz)		4	kV
Debuncher RF			
$h = 1$ (588 kHz)		40	kV
$h = 4$ (2.35 MHz)		250	kV
Beam at Target:			
final bunch length	15	40	nsec, rms
final bunch intensity	1×10^{12}	4.3×10^7	
final momentum spread	2	8	10^{-3}, rms
transverse emittance	15	< 15	π mm-mrad, norm., 95%

4.2 Work Breakdown and Cost Estimates

Cost estimates forthcoming...

Figure 12: Spreadsheet of estimated costs to configure Fermilab complex to deliver proton beams to the g-2 and $\mu 2e$ experiments.

4.3 Schedule

Example of possible schedule, forthcoming...

Figure 13: Example of a possible schedule for Fermilab complex to deliver proton beams to the g-2 and $\mu 2e$ experiments.

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`http://www-accel-proj.fnal.gov/Proton_Plan/index.shtml`.

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