# Design and Cost Update for Proposal P-989

*The New (g-2) Experiment: A Proposal to Measure the Muon Anomalous Magnetic Moment to ±0.14 ppm Precision*

## The New g-2 Collaboration*

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**Rendering of the proposed g-2 Conventional Facilities; Courtesy FESS.**

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# Overview of g-2 and statements by PAC

The purpose of this report is to update the PAC on the g-2 scientific case and to respond specifically to questions raised in the subsequent letter (attached) from Lab Director Pier Oddone to the Collaboration. Three main issues—as identified by the PAC—are included in Pier's letter:

1) The impact and technical implications with respect to other aspects of the Fermilab program;

2) The need to develop a mechanism to draw upon the technical expertise at BNL from the previous BNL g-2 experiment;

3) A validity of the costs and schedule estimate, which are significantly reduced from what P5 considered.

We address each of these in turn in the following report; however, we begin with a brief update on the physics situation and a synopsis of the experimental plan.

## *Physics Update*

Two recent developments affect the confrontation between the Standard-Model theory and the measured value of $a_\mu$: New data from BaBar[1] on $e^+e^- \to \pi^+\pi^-\gamma$ have become available. These data impact the 1$^{st}$-order hadronic vacuum polarization (HVP) contribution, as determined in the dispersion relation

$$a_\mu\left(\text{HVP}\right) = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{4m_\pi^2}^{\infty} \frac{ds}{s^2} K(s) \left(\frac{\sigma\left(e^+e^- \to \text{hadrons}\right)}{\sigma\left(e^+e^- \to \mu^+\mu^-\right)}\right)$$

where the last term in parentheses on the left-hand side is the ratio $\Re(s)$. Secondly, a new value for the ratio of the muon-to-proton magnetic moments is recommended in the most recent CODATA global summary.[2] This ratio impacts the extraction of $a_\mu$ from the experimentally measured quantities.

In contrast to the beam energy scans carried out for the $\Re(s)$ measurements at Novosibirsk, the BaBar collaboration operated at fixed energies near 10.6 GeV, and used initial-state radiation (ISR) to tag the energy of the collision. This ISR method has also been used at Frascati by the KLOE collaboration, where the machine is optimized for the $\phi$ resonance. Because of the higher energy of the PEP-2 collider, the BaBar data cover a much larger energy range, and the (hard) initial-state photon is detected. Furthermore, the BaBar collaboration measured $\Re(s)$ directly; i.e., the cross section for $\pi^+\pi^-/\mu^+\mu^-$, which is the quantity that goes into the dispersion integral above.

These data have been incorporated into a new global analysis[3] by Davier, et al. The result is shown in Fig. 1. The lowest two points represent the pre- and post-BaBar situation. The central value of the theory has moved downward. Including all contributions, the Standard-Model value is now $a_\mu\left(\text{SM}\right)=116\ 591\ 834\ (2)\ (41)\ (26)\times10^{-11}$, which with its total error of $49\times10^{-11}$, is about 30% smaller than the experimental error of $63\times10^{-11}$.

The release of the BaBar data represents an important milestone in the present round of $\Re(s)$ measurements. Except for the final data set of the KLOE collaboration, all data have been published on the $2\pi$

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[1] B. Aubert, et al., (BaBar Collaboration) arXiv:0908.3589v1, Aug. 2009, submitted to Phys. Rev. Lett.

[2] P.J. Mohr, B.N. Taylor and D.B. Newell, CODATA Group, Rev. Mod. Phys. **80**, 633 (2008).

[3] M. Davier, A. Höcker, B. Malescu, C.Z. Yuan and Z. Zhang, arXiv:0908.4300, submitted to Eur. Phys. J.

channel, which dominates the contribution to $\Re(s)$. New efforts are underway at Novosibirsk with VEPP-2000, and the Belle collaboration is looking at multi-pion final states using ISR.

The recent CODATA Tables[2] report a new value for the ratio $\lambda = \mu_\mu / \mu_p$, which provides the conversion between the two experimentally measured frequencies in the muon (g-2) experiments: $\omega_a$ and $\omega_p$ that represent the muon spin precession frequency and the magnetic field calibrated to the Larmor precession frequency of a free proton. The anomaly is obtained from $a_\mu(\text{E821}) = R/(\lambda - R)$, where $R \equiv \omega_a / \omega_p$. The change in $\lambda$ increases the experimental value by $9 \times 10^{-11}$ with the same error, namely a shift of 0.14 standard deviations.

Using the latest Standard-Model value from Davier et al.[3] and the experimental number calculated with the updated $\lambda$, we get $\Delta a_\mu(\text{Expt - SM}) = (255 \pm 80) \times 10^{-11}$, or a 3.2 $\sigma$ difference, using the $e^+e^-$ data to determine the lowest-order hadronic contribution. These latest results presented in Fig. 1 and Table 1. The goal of the Fermilab experiment is an error on $a_\mu$ of $16 \times 10^{-11}$. With no further improvement in theory and the same central value for $a_\mu$, $\Delta a_\mu$ would reach the ~5 $\sigma$ level. On the timescale of our new measurement, additional data on $\Re(s)$ along with additional theoretical work on the hadronic light-by-light contribution should further reduce the uncertainty on the Standard-Model value.
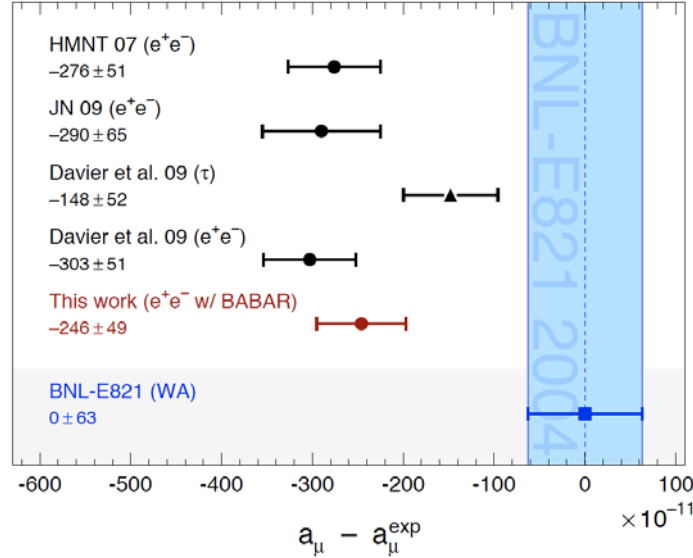


Fig. 1 Various evaluations of the lowest-order hadronic contribution to $a_\mu$ obtained from $e^+e^-$ annihilation into hadrons and from hadronic tau decay. The red (recommended) point uses all $e^+e^-$ data, while the black point above it does not include the BaBar result. (From Ref. [3])

One other development is a new look at the isospin breaking corrections that are needed to use the spectral functions from hadronic $\tau$ decays, and CVC to determine the hadronic contribution.[4] Since the $e^+e^- \to \pi^+\pi^-$ reaction goes through the neutral $\rho$ meson, and the weak decay $\tau^- \to \pi^-\pi^0\nu_\tau$ goes through the charged $\rho$, isospin corrections are important. The isospin corrections presented in Ref.[4] decrease the disagreement between independent CVC tests, but a systematic difference of about 2.3 $\sigma$, remains

(see Fig. 6 of Ref.[4]). A contrasting point of view is presented by Benayoun et al.[5] The isospin breaking calculations necessary to use the $\tau$ data to extract $a_\mu^{Had}$ are still a topic of active work.

The hadronic contribution to $a_\mu$ will be one of the central topics discussed at the PHIPSI2009 meeting in Beijing in mid-October, where many of the principal players will be in attendance. We will update this discussion at our PAC presentation in November if any new results are presented.

| Quantity | Value | Error | Reference |
|---|---|---|---|
| $R$ (E821) $= \omega_a/\omega_p$ | 0.003 707 206 3 | 20 x10$^{-10}$ | Table XV of Phys Rev D73 072003, 2006 |
| $\lambda = \mu_\mu/\mu_p$ | 3.183 345 137 | 85 x10$^{-9}$ | CODATA 2006 |
| $a_\mu$(E821) $= \dfrac{R}{\lambda - R}$ | 116 592 089 x 10$^{-11}$ | 63 x10$^{-11}$ | E821, updated with new CODATA $\lambda$ |
| SM ($e^+e^-$) | 116591834 x 10$^{-11}$ | 49 x10$^{-11}$ | Davier et al; post BaBar and re-analysis of $e^+e^-$ data arXiv:0908.4300 |
| Expt – Thy | 255 x10$^{-11}$ | 80 x10$^{-11}$ | 3.2 $\sigma$ |

Table 1 BNL E821 measured quantity $R$, which is defined as the ratio of the anomalous precession frequency $\omega_p$ to the event-weighted magnetic field; the latter is expressed as the Larmor frequency of a free proton, $\omega_p$. The anomalous moment is given by $a_\mu = (g-2)/2$. The published averaged $R$ value in Table XV of the 2006 PRD includes the systematic errors of the relative entries from the individual running periods.

## *Experimental Plan*

The BNL determination of $a_\mu$ has an uncertainty of 0.54 ppm, which is dominated by the statistical error of 0.46 ppm. Proposal P-989 describes a plan to use the Fermilab complex of accelerators and beamlines to deliver a greatly increased integrated number of stored muons into the relocated storage ring that was used at Brookhaven. The plan aims for a final uncertainty on $a_\mu$ of 0.14 ppm, derived from a 0.10 ppm statistical sample and roughly equal 0.07 ppm systematic uncertainty contributions from measurement of the magnetic field and from measurement of the precession frequency. Twenty-one times more events are required compared to the E821 experiment. Our experiment can run parasitically with the main injector neutrino program, using proton batches from the Booster that would otherwise go unused. After re-examination of the plan in the past summer, we continue to believe that our statistical goal can be achieved for positive muons in less than 2 years of running. A follow-up run using negative muons is possible, depending on future scientific motivation. Owing to the reduced negative pion production cross section from an 8-GeV proton source, the increased intensity from Project X would be greatly welcome, and could be used without modification of our plan. In addition to the muon anomalous magnetic moment, we are designing a dedicated system of detectors that will enable a measurement of the muon's electric dipole moment with a precision improvement compared to recently published work[6] of up to two

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[5] M. Benayoun, P. David, L. DelBuono and O. Leitner, arXiv:0907.5603v2, Aug. 2009, and references therein. Their first paper, on this topic was published in Eur. Phys. J. C 55, 199 (2008).

[6] (Muon (*g*-2) Collaboration) G.W. Bennett et al, Phys. Rev. D 80, 052008 (2009).

orders of magnitude. The g-2 data can also be used to improve the limits on Lorentz and CPT violation in muon spin precession (see, for example, Ref. [7] by the E821 Collaboration).

The key improvements at Fermilab compared to Brookhaven are the higher rate of muon fills per second, slightly higher stored muons per fill, much lower background pion contamination per fill, and a longer anticipated running period. The 15-Hz Booster upgrade is central to the operation, which then uses six batches out of a sequence of 20 for the g-2 operation. Each batch is subdivided using RF in the Recycler to prepare four short proton "bunches," which are directed to the existing antiproton target in the AP0 building. Here, the target, lithium lens, and pulsed dipole (PMAG) were assumed in our Proposal to be useable for production of 3.1 GeV/c pions. These pions would be directed down the AP2 transfer line, around the Debuncher, and re-directed back toward the AP0 building along the AP3 transfer line. A new building to house the storage ring would be built close to the AP0 target building and adjacent to the AP3 transfer line. A new "beamline stub" is required to elevate the beam to the surface from AP3 and into the storage ring. This plan is essentially unchanged from the proposal; however, many details are now worked out so that costing and technical risk uncertainty can be lowered. The preliminary optics have been designed end-to-end and confirm that the Fermilab accelerator complex can meet the needs of the experiment with modest upgrades. We describe our work below.

The new experiment will require upgrades and maintenance on several components of the storage ring and a new suite of segmented electromagnetic calorimeters and position-sensitive detectors. A modern data acquisition system will be used to read out waveform digitizer data and store it so that both the traditional event mode and a new integrating mode of data analysis can be used in parallel. Improvements in the field-measuring system are also required. They will both follow well-developed upgrade plans and address challenges for even further precision through a program of R&D efforts. These tasks are being addressed, but none represent major cost drivers for the experiment. We do not comment extensively on this work at this time.

A challenging aspect of the new experiment remains the disassembly, transport, and reassembly of the BNL storage ring. As outlined below, lead project engineers from Brookhaven have helped develop a detailed plan of construction steps that includes specific labor estimates for engineering and technician time on a week by week basis for assembly of the storage ring over an 18-month period. The plan is based on the well-documented work carried out to assemble the ring originally.

As outlined below, one of the major completed tasks has been the design of the g-2 Conventional Facilities. As presented by FESS, the conventional construction of the building can begin immediately on completion of the current Tevatron run, which we assume ends Oct. 2011. Assuming advanced design work, prior to the shutdown, it will take 9 months to complete the g-2 Conventional Facilities, leading to beneficial occupancy in summer, 2012. At this time, the storage ring components can be moved into the building and the 18-month assembly can begin. The shimming of the magnetic field will take up to 9 months, after which operation with beam can begin for physics. This *technically driven schedule* has the experiment beginning in the latter half of 2014.

The Collaboration remains enthusiastic and strong; however, it is imperative to obtain Stage-1 approval soon so that both our international and domestic collaborators can seek funds that will permit them to devote significant effort and resources to the g-2 experiment. Without official approval, these groups are unable to commit or do significant work.

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[7] (Muon (*g*-2) Collaboration) G.W. Bennett et al, Phys. Rev. Lett. 100, 091602 (2008).

## *The New g-2 Experiment within the FNAL Program*

Timing of the New g-2 Experiment fits in well with the Fermilab program, which envisions the Tevatron Run II turning off at the end of FY2011, with the neutrino program continuing off of the Main Injector for MINOS, MINERvA, and NOvA. At this point, assuming no further antiproton production is required, the Accumulator, Debuncher, and associated beam lines will become available for use with g-2. These same systems are also part of the plans for the Mu2e experiment, which would come on line around FY2016-2017. Thus, a ~4-5-year window of opportunity exists in which the muon g-2 measurement could be performed. While the MicroBooNE and muon g-2 experiments both require 8-GeV pulses from the Booster, the needs of both experiments can be met with the planned 15-Hz upgrade. The 15-Hz upgrade will ensure reliable delivery of the 9 Hz that can be maximally utilized by the NuMI/NOvA program. At current Booster intensities of $4 \times 10^{12}$ protons per pulse, assuming an 80% live time, the remaining 6 Hz available equates to a total of $6 \times 10^{20}$ POT available per year for 8-GeV programs running in parallel to NOvA. For comparison, the MicroBooNE proposal called for $6 \times 10^{20}$ POT delivered over 3 years, while the muon (g-2) program requires an integrated luminosity of $4 \times 10^{20}$ POT. With the 15-Hz upgrade, the integrated luminosity required for both programs in principle could be achieved within two years.

While the Mu2e and Muon g-2 experiments would not be able to run simultaneously as currently envisioned, the two experiments can run in a leap-frog fashion with less than one month shutdowns between transitions. However, the goal is to complete the Muon g-2 experiment prior to Mu2e commissioning and avoid this situation. This goal appears quite reasonable given the anticipated start dates of the two experiments.

It should also be pointed out that while the g-2 experiment could benefit from higher proton flux from the Recycler via Project X with essentially little-to-no upgrades required of the beam lines or experiment infrastructure, other than targeting or other considerations concerning high particle throughput. Accordingly, it is easy to envision the use of the g-2 building and infrastructure for future experiments, such as a dedicated muon electric dipole moment measurement.

# Cooperation with BNL

The Fermilab Program Advisory Committee recognized the strong need to utilize the long experience built up at the BNL during the construction and operation of E821 in their statement: *Also, it would be useful to develop mechanisms to draw upon the technical expertise developed at BNL over many years during the previous (g-2) experiment.*

We have been in close contact with the BNL Associate Laboratory Director for High Energy and Nuclear Physics, Steve Vigdor, who has been very supportive of the physics goals proposed for the Fermilab muon (g-2) experiment. He supports our efforts to move the apparatus to Fermilab. With his blessing, we have begun conversations with the BNL engineers and technicians who were key players in the construction and operation of the storage ring.

Members of our Collaboration recently visited BNL and had extensive conversations with engineers Chien Pai and Lou Snydstrup, along with John Benante, who supervised the storage ring construction, and Don von Lintig, who was the lead technician in assembling the storage ring magnet, vacuum systems, and other systems. A detailed 30-point assembly plan was drawn based on the actual BNL documentation on the E821 ring construction. It was possible to detail tasks and manpower needed, along with the time

each step will take. This detailed plan reduced the re-assembly cost, and firmed up the re-assembly schedule, as discussed elsewhere in this report.

A visit with Steve Vigdor and the P-989 co-spokesmen affirmed the general agreement that the E821 equipment would be available for a Fermilab experiment. Also discussed was how BNL could participate in the moving of the ring and the exchange of expert information. In answer to the PAC's questions, Steve prepared the following statements:

> *Brookhaven will make available all experimental equipment related to the E821, Muon g-2 Experiment, which includes the Storage Ring, its components and power supplies and the g-2 specific beamline elements. We understand that the costs to disassemble, ship and re-assemble the equipment are part of the TPC presented by the collaborators.*

> *Many experts at Brookhaven contributed significantly to the success of the E821 experiment and we recognize that they will need to be called on from time to time for critical information sharing and advice to smoothly aid in the relocation of the experiment to Fermilab. We envision support for very short periods of time and for communications; however, if significant time is required, we expect the costs will be covered from funds requested as part of the project, and scheduling of the work cannot be allowed to disrupt essential contributions made by the relevant staff to ongoing RHIC/AGS operations and upgrades. For these reasons, we also require that all requests for effort from staff of the BNL Collider-Accelerator Department (C-AD) be made to the C-AD Chair (currently Derek Lowenstein), rather than directly to the staff member(s) involved.*

We were also assured that lead physicists Bill Morse and Yannis Semertzidis will continue their association with the New g-2 experiment. They are experts on various parts of the experiment, and their continued participation is necessary and highly desirable.

# Design and Cost Issues, Revisited

## Overview

The bulk of this report addresses the re-assessed costs of the experiment. In our Proposal, we identified three budget categories:

1) **The 8-GeV proton complex**. Upgrades and modifications to the existing proton complex are required to produce proton bunches for g-2 and for delivery of 8-GeV protons for other Laboratory initiatives. We listed these cost estimates in our Proposal, but our Collaboration did not specifically work on these estimates as they were provided as part of a package related to the facility. We believe they are not specific to g-2 as they are necessary or beneficial to the NOvA, Mu2e and microBooNE programs as well, and perhaps others. These costs include the 15 Hz Booster upgrade, the connection of the MI-8 transfer line to the Recycler, RF in the Recycler for bunch formation, the kicker system required to extract beam from the Recycler to the P1 beam line, and the removal of beam cooling systems and other aperture restrictions within the beam lines and antiproton rings prior to their re-use in Mu2e and g-2. Of these categories, the RF in the Recycler may be exclusive to g-2, depending on the final proton plan for Mu2e operation. The g-2 Collaboration has not reviewed any of these costs, many which have long been established for the NOvA and Mu2e programs, with some recently advanced by funding for the rapid construction of NOvA. We do not include them in our Total Project Cost.

2) **The non-DOE funded experimental equipment**. These costs are associated with new or upgraded detectors, electronics, DAQ and magnetic field measuring equipment, which will be provided principally by the non-Fermilab Collaborating institutions. Funding is anticipated through NSF and foreign contributions, although one item—the straw detector system—is being actively pursued by a Fermilab Wilson Fellow and, as such, we add this portion of detector funding to the DOE-funded category below. This was previously assumed to be funded by outside sources. We assume that a new inflector magnet will be provided by our Japanese collaborators, who built the existing magnet used in E821. Of course, full approval will be required before any MOU can be pursued on this matter. The estimates for these costs have not been updated; however, we briefly summarize R&D progress.

3) **The DOE-funded g-2 experiment and beamlines.** This is the main cost-driver category for the experiment. It includes the g-2 Conventional Facilities, the relocation of the storage ring from BNL to Fermilab, and the preparation of experiment-specific beamlines. Each of these has been examined in detail and we report on our findings.

## History

In April, 2009, lab management established an independent committee led by Ron Ray to estimate the costs of the proposed g-2 experiment – all three categories above. The central charge to the "Ray Committee" was:

> The Committee is asked to evaluate costs and schedule for implementing the (g-2) experiment proposal, and consider possible conflicts with other parts of the Fermilab program. This review should cover both those costs listed directly as part of a (g-2) project, and those, which may be considered as general infrastructure and used for more than just a (g-2) experiment. It is critical that the Laboratory understand the costs and schedule issues to proceed in its consideration of the (g-2) proposal.

While the Committee largely worked alone, they did consult g-2 Collaborators and one member was part of the BNL g-2 engineering team. The Committee arrived at several major conclusions, which were subsequently addressed. The Executive Summary states:

> We find that the cost estimates for moving the muon storage ring to Fermilab and for building new detectors are generally reasonable, in large part because of the groups extensive prior experience. However, we feel that the cost and complexity of the accelerator modifications have been underestimated. Given the time and resources that g-2 has been able to devote to this exercise, this is not unreasonable as a considerable amount of work will be required to fully develop a cost estimate for this complex task. In addition, we feel that the cost of the building has been underestimated.

The Ray Committee identified *potential* areas for increased costs compared to our proposal estimates. It is instructive to examine the main changes, which pertain to the DOE experiment-specific costs (Category 3 above), and address them directly. The five items are:

1) $2 M for items not part of the Proposal estimate. These include funds for a new storage ring kicker, and funds for the *installation* of the new superconducting inflector magnet. Additionally, $0.5 M was assigned for a possible CBO damping scheme, but this cost will be removed because, at present, no design exists and it is not clear that such a system is required. Once designed and simulated—an interest of our Novosibirsk colleagues—the benefit of such a system can be evaluated, and its implementation can be studied.

2) $3 M for Project Management costs. This estimate is based on similar sized projects at Fermilab.

3) $4-8 M for an increased estimate of the building based on uncertainties on the specific site and on a lack of a real design for the facility in general.

4) $3.1 M for the AP0 target region.  This is largely based on uncertainty as to whether the existing lithium lens can operate at the proposed 18 Hz average rate (80 Hz instantaneous bursts) and whether a lengthy R&D effort would have to begin to develop a new lens.  It also assumes a new target and a new PMAG will have to be built.

5) $4.0 M largely for ~100% level contingencies for the conventional accelerator and beamline improvements that are required to deliver the beam to the g-2 storage ring and for diagnostics and radiological issues.  The increased contingencies reflect the lack of a detailed beamline design at the time of the Proposal.

Subsequent discussions with Lab Director Oddone led to a Collaboration-led design and cost update exercise over the summer, which was focused on areas having the greatest uncertainties.  This effort was partially supported by the lab, especially for the FESS engineering of the g-2 Conventional Facilities.  We have found many cost savings in this exercise, not only for the categories above, but also for uncontested original estimates, such as the cost of re-assembling the storage ring.  In addition, this work has led to reduction in design-related contingencies, especially with respect to the required beamline work.  We address the work accomplished to date below and summarize their costs in Tables 4 – 6  at the end of the document.  Table 7 gives a compact roll-up of costs.

## g-2 Conventional Facilities

Under the direction of Russ Alber, a team of FESS engineers has produced a detailed project definition report (PDR) for the Muon g-2 Conventional Facilities, which includes the civil construction required for both the building and the beamline enclosure.  This report is the result of a concentrated collaboration between project physicists, Brookhaven experts, and FNAL engineers, to design a building and beamline enclosure that will meet the design criteria required for the experiment.  Gross features of the building plan include a high-bay experimental area to house the g-2 storage ring, a loading dock, and a 30-ton overhead crane; a low-bay service building that contains a control/counting room; a mechanical area for building infrastructure; a power supply area for beamline and inflector magnet power supplies; and a restroom.  Two parking areas are provided, a small paved lot at the west corner of the building near the control room, and a much larger compacted gravel hardstand to the southeast that doubles as a storage area for the g-2 cryostats during the ring construction phase.  Figure 2 shows an architectural floor plan of g-2 Conventional Facilities.

*Site Considerations-*

The site for the experimental hall is located on Kautz road approximately 100' southeast of the AP0 target building.  The coarse-scale placement of the building on the FNAL site is dictated by the need to maintain a reasonable distance back to the AP1 tunnel, which will house the final portion of the muon beamline.  From the AP1 enclosure, a new three-stepped beam enclosure brings the beam up 18' to the surface over a 50' horizontal run.  The exact position along AP1 has been optimized to minimize disruption of utilities and drainage, and by considering where the muon beam can most conveniently be brought out of the AP1 tunnel and up to the surface.  The elevation of the building floor is 4' below the grade of Kautz road, which matches the natural contour of the land (thus minimizing excavation and fill) and has the added benefit of placing the plane of the storage ring slightly below grade (thus reducing radiation concerns).  The proximity of Kautz road allows convenient access for trucks to deliver materials to either parking lot or directly to the high-bay via the loading dock.  The site also allows convenient access to an
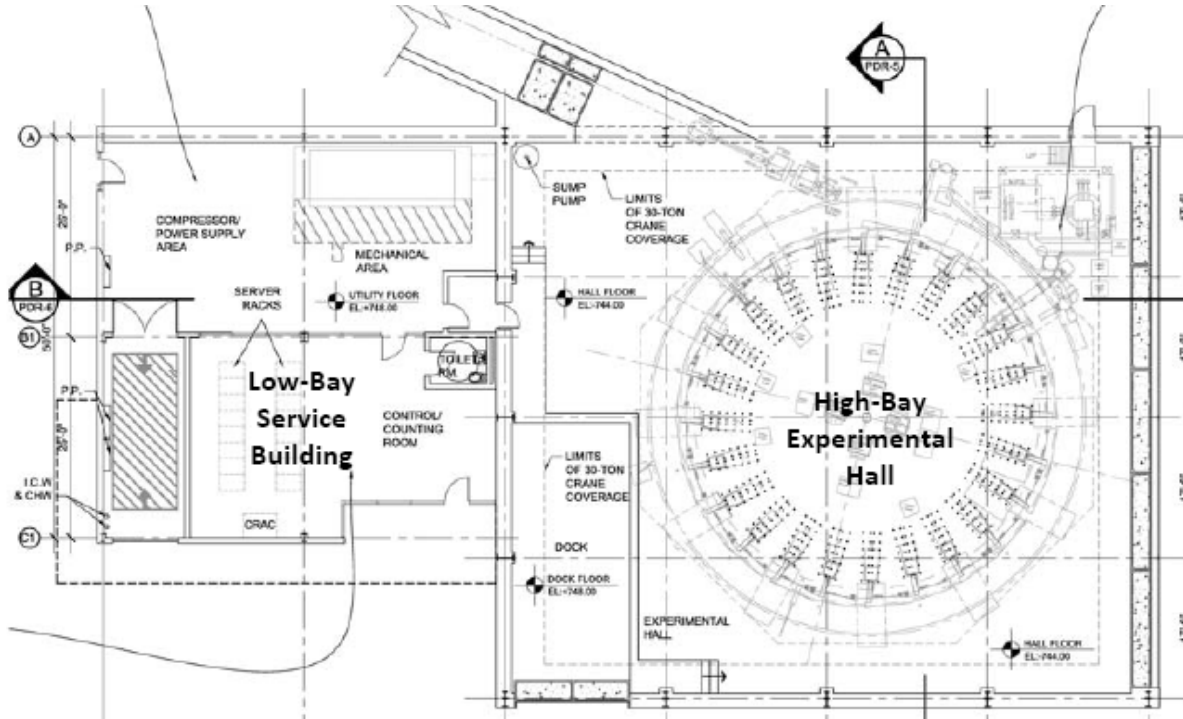
Fig. 2 Architectural floor plan of g-2 Conventional Facilities

electrical feeder for a new 1500 kVA transformer and all other utilities including ICW. The proximity to the Tevatron enables cryogenic needs to be met with largely existing infrastructure.

*High-Bay Experimental Hall-*

The high-bay experimental hall has been designed to meet the needs of the muon g-2 storage ring in several capacities. The 56' outer diameter of the ring yoke requires a building with a larger clear span than most FNAL buildings. The overall dimensions of the bay are 70' x 80', which is approximately 5' larger in either dimension than the building currently housing the storage ring at Brookhaven. A loading dock in the building provides full access for flatbed trucks to be offloaded directly using a 30-ton bridge crane. The heaviest pieces of material or equipment that need to be moved are the 24 bottom and top plates of the return yoke, each of which weighs 25 tons.

The overall weight of the storage ring is 650 tons. In order to meet the floor stability requirements a novel design has been developed where the storage ring is installed on an octagonal platform that is independent from the rest of the building. The platform is formed from 2.5' thick reinforced concrete and sets on an array of eight 4' diameter caissons down to bedrock. A similar construction method of using caissons down to bedrock is used to support each building pillar.

One of the experimental concerns arises from temperature stability in the hall. The C-shaped storage ring can open and close with temperature variations thus perturbing the field. Even worse, differential heating of one portion of the ring can cause parts of the magnet gap to change relative to others. It was found that with proper building insulation and thermostat settings, a conventional HVAC system can maintain the +/- 2F experimental requirements. A stratification and distribution system has been designed to ensure differential heating of the storage ring is avoided.

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*Low-Bay Service Building-*

The low-bay service building serves two purposes. It provides a temporary working area outside of the high-bay area during the construction phase of the experiment, as well as meeting the needs of the experiment during operation. The building is divided into two major areas. A mechanical area on the back towards the beamline provides the space needed for building infrastructure including fire protection and HVAC. The same area houses the powers supplies for the superconducting inflector and beamline elements required to bring the muon beam to the surface and produce the final focus into the storage ring. The front half of the low-bay building includes a restroom, control room, and counting house for the detector electronics, data acquisition, NMR readout, surface coil power supplies, and magnet controls. For now shifts are expected to be staffed in the low-bay surface building.

*Beam enclosure-*

The beam enclosure brings the muon beam from the AP1 beamline up to the Muon g-2 surface building in a series of three 6' steps. The costing contains all elements of the civil construction, but beamline elements are included elsewhere in the proposal. Since the AP1 tunnel will still be used to transport 8 GeV protons to the AP0 target, it is necessary to maintain 21' dirt-equivalent radiation shielding along any line of sight. In order to maintain these shielding needs, the top of the last step in the enclosure is capped by a 4' slab of steel. The current berm above AP1 will be extended horizontally to meet the raised 2' thick concrete wall that forms the back side of the Muon g-2 building.

*Cost and Schedule-*

A detailed set of costs is provided in the PDR included in the Appendix. The construction cost for the building is estimated to be $4.0M, which translates to $6.55M with indirects, EDIA, and management reserve included. Although there is a high probability it can be waived, for now an additional $450k has been added in compliance with DOE space management regulations, bringing the total project cost to $7.0M for the civil construction of the building and beam enclosure.

The original cost of the building, as presented to the March PAC, was estimated at $4M based on preliminary conversations with FESS. More detailed conversation during the summer and an initial spreadsheet of cost was developed in conjunction with the Ray review, which led to an estimate of $8M for the total building cost. Over the last several months a much more detailed PDR has been developed by FESS in conjunction with project physicists. The final cost of $7M is close to the value quoted by the Ray review and is slightly lower due to several cost saving considerations including optimizing the building on the site, reducing the crane capacity from 40 to 30 tons, and reducing the span of the building from 80' to 70' in the direction orthogonal to the crane travel.

Due to the proximity to the AP1 beamline, civil construction of the beam enclosure should coincide with the next extended shutdown. With the Tevatron expected to run through the end of fiscal year 2011, a reasonable start date for civil construction is October 2011. This date of October 2011 serves as a linchpin around which the rest of the project timeline can be established. For the building and beamline civil construction, a total of 15 months of lead time is needed to finalize the preliminary design, start the project, and finish all the required engineering. Once construction starts, beneficial occupancy of the building is expected 9 months later. By this schedule, the next stage in the design work must begin in the summer of 2010, and the ring can begin its 18 month estimated assembly period in the summer of 2012.

# Beamline Design Update and Costing

The Ray Committee recognized the nascent status of our beamline design. The individual sections include the pion production target region, the decay FODO in AP2, the transfer around the Debuncher and along the AP3; and finally, a new "beamline stub" that couples to the storage ring. Accordingly, our Proposal budget was typically increased to 100% contingency or more pending real work on these sections. The properties of the target region, the decay lattice design and the transport to and injection into the g-2 ring are tightly coupled, so that a full end-to-end simulation is required. During the last months the collaboration has made significant progress in this direction by forming a "Beam Team" between members of the Fermilab accelerator division, the antiproton group and the universities, where new work is presented and discussed in weekly teleconferences. While we have not yet completed a full end-to-end simulation, each piece has been modeled in a manner compatible with the overall acceptance of the storage ring. From this ongoing work, we can more confidently estimate the budget and assess remaining risks.

*Target Region-*

With the help of the Antiproton Source Department and Mechanical and Electrical Engineering Departments of the Fermilab Accelerator Division, much work has been done to understand the target region for the g-2 experiment. At present two plausible scenarios are foreseen, one using the existing target system with upgraded power supplies for the lithium lens and pulsed dipole magnet, and a second system using a doublet quadrupole arrangement and dipole magnet running DC. In any scenario, the existing antiproton target itself is sufficient for use at the 8.9 GeV/c impinging beam energy and would be used for the g-2 experiment.

### *Plan A*

Fermilab has over 25 years of experience using a lithium lens and pulsed dipole magnet in the target vault for antiproton production. The lens, which pulses approximately 62 kA into the primary of a current transformer (x8 in the secondary coil), produces a 360 µs-wide pulse every 2.2 seconds at its present operating condition. The heat load on the lens system from ohmic heating at this current is ~4 kW, while the heating from the beam—operating at a beam power of 70-75 kW—is ~2 kW. The capacity of the system is on the order of 10-11 kW.

Simply scaling the beam line elements from 8.9 GeV/c operation to 3.1 GeV/c operation yields a factor of 1/2.8 less current necessary for the lens, or 1/8 of today's power. The ohmic heat load at 2.2 s cycle time would thus become 490 W. Scaling from these conditions to the g-2 experiment's baseline of 18 Hz, with 25 kW beam power, the total load would be 20 kW, or twice the system capacity. Reducing the power by another factor of 2 (or, current by another 30%), would reduce the total heat load to just under 10 kW, within the present system's capabilities. There is some adjustment possible in cooling water flow as well.

At this further-reduced current, it is estimated that the pion yield would be reduced from the original estimates by ~27%, assuming the lens is positioned further from the target at its longer focal length. Thus, the run-time of the experiment would be extended accordingly, all else being held constant, in this scenario.

The lens, its transformer, and the pulsed dipole magnet could all be used with appropriate power supplies to run them at the much-increased frequency. The costs of the magnetic elements are well known.

## Target Vault Modules

Proton Direction →

10 3/4" 10 3/4" 10 3/4" 10 3/4" 10 3/4" 10 3/4" 10 3/4" 10 3/4" 10 3/4" 10 3/4" 10 3/4" 22 1/4" 10 3/4"

Target SEM  Target  Collection Lens  Collimator  Pulsed Magnet

7/8" 9/16" 9/16" 9/16" 9/16" 9/16" 9/16" 1 1/4" 1 1/2" 9/16" 1" 9/16" 9/16"
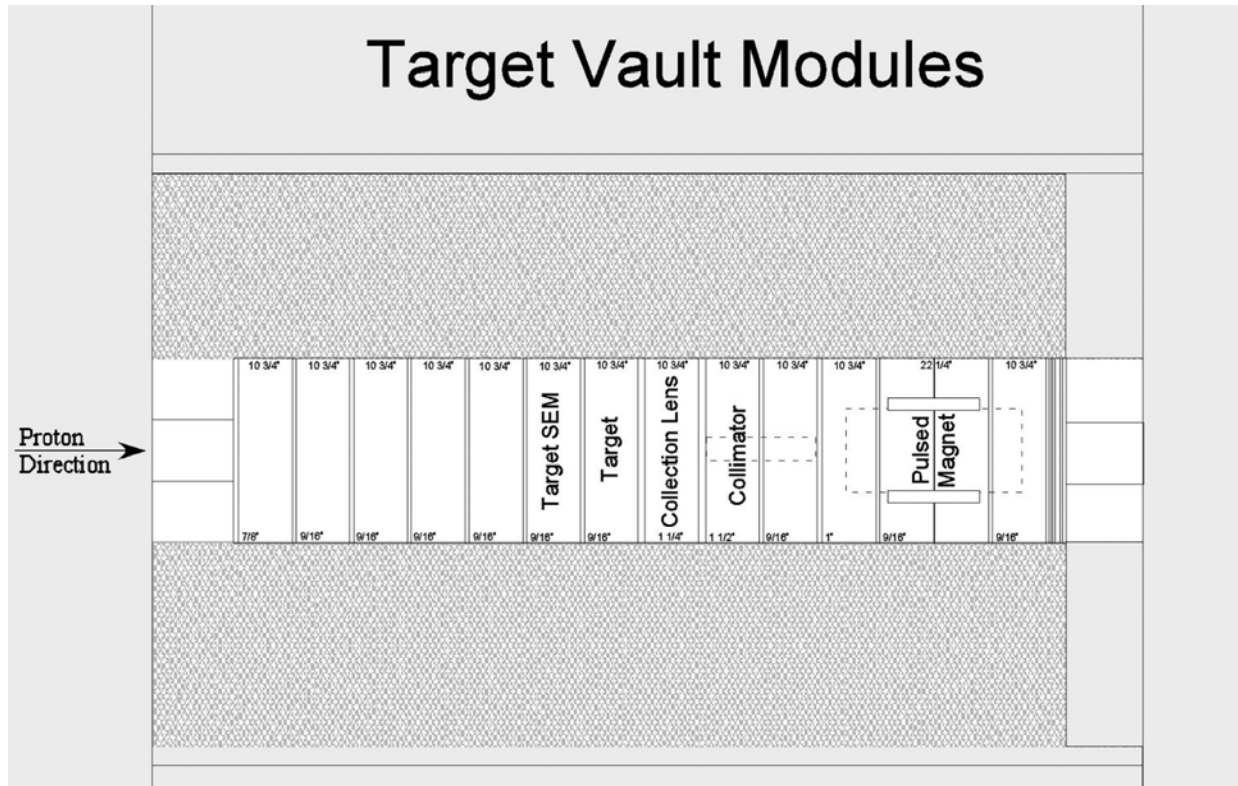
Fig. 3. Schematic layout of the AP0 target vault at Fermilab, with present module uses identified.

Work has been performed in the Accelerator Division at Fermilab to scope out the costs of the required power systems. Estimates are provided in the cost tables, representing actual design elements to produce the bursts of 80 Hz pulses at an average rate of 18 Hz for the experiment.

The cost estimate also includes funds for an ANSYS analysis and hardware test of a lithium lens system running under simulated g-2 conditions. Though the power fed to the system will be reduced by over a factor of 16 and the beam power reduced by a factor of three, the lens will be pulsed at a rate higher than today by a factor of roughly 36. The fatigue in the system will be different for more-frequent, gentler pulses than with today's less-frequent, higher energy pulses. This analysis will aid in the understanding of possible failure modes and lens component lifetimes.

### Plan B

A secondary plan is being developed for the target area for g-2 in which the pulsed lens and magnet system would be replaced by a set of radiation-hard magnetic elements that could run at DC currents. This was the approach taken at BNL for g-2, where the average beam power on target was three times higher and in which the magnets survived this radiation environment for the life of the experiment there. Figure 3 shows a plan view of the Fermilab target vault at AP0. The 32.25-in wide by 10.75-in-long modules hold the various elements in place from above. Within this available space one could conceive of placing the target (presently at the middle of the vault) at the most upstream position followed by a doublet quadrupole set made of radiation-hard components as was done at BNL. In fact, the length and width of the BNL magnets are small enough to fit inside the space provided, and the design for these magnets is available. A DC dipole magnet would then be placed with its bend center in the same location as the center of today's pulsed magnet to set the trajectory downstream.
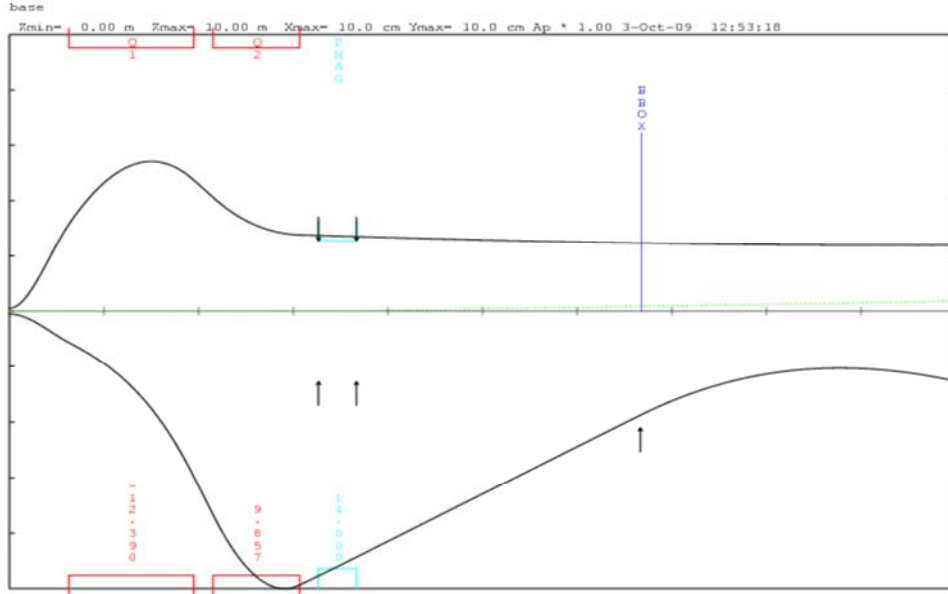
Fig. 4. Optics calculation showing beam envelope from the target through a quadrupole doublet, using the BNL experiment's magnet parameters. The required location of the 3-degree bend magnet is shown just to the right of the quads.

A preliminary layout using BNL-style quadrupoles has been performed, as indicated in Fig. 4.

While all of the equipment used in the BNL g-2 experiment is available for use in the FNAL version, these first two quadrupoles—Q1 and Q2—are activated and very likely would not be transported to Fermilab. However, advantage could be taken of the existing designs, drawings and actual costs of these quadrupoles once a preferred beam optics design is obtained.

Both plans are likely similar in cost, where one is trading low magnet costs but high power supply costs in Plan A for larger magnet costs but lower power supply costs in Plan B. A major benefit of Plan B would be the potential for better reliability and less maintenance for a DC system. But Plan A is a better understood system at this point and presents only a small hit on run time. It could turn out to be appropriate to begin g-2 running with a Plan A target system using mostly lens equipment that exists at the end of Run II, followed by an early upgrade to Plan B for full production running.

*Target to Debuncher-*

The current AP2 lattice has a large transverse (unnormalized) acceptance of about 35 mm mrad in both planes, which matches well to either the Li lens or the quadrupole collection of pions from the target region. The lattice for this line has been translated into MAD, TRANSPORT and DECAY TURTLE input decks and is shown in Fig. 5, top panel. As described in the proposal, for the generation of muons with $p_\mu$=3.094 GeV/c in pure forward decay kinematics, an initial pion momentum of $p_\pi$=1.005 $p_\mu$ is required. However, pions with 3-4 % higher momenta decaying with muon angles of several mrad can still contribute to the magic muon flux. Thus, in order to increase the muon flux, (i) the FODO beta function, i.e. the pion beam size, should be decreased in the decay region and (ii) a momentum bin of ±2% should be accepted by the lattice. Modification (i) reduces the beta function, i.e. pion beam size, in the decay FODO, so that larger decay angles still remain within the acceptance of the g-2 ring. The momentum acceptance is limited by second-order chromatic effects, where a large aperture Q1, Q2 collection system is likely to

be less efficient than the Li lens, which demonstrated 2.5% momentum acceptance as an antiproton source. One should emphasize that these FODO changes are required only for the decay region, because their importance is weighted by the $e^{-z/L}$, where L=173 m is the decay length of pions of $p_\mu$. Thus reducing the beta function in the first ~150 m long straight section of the AP2 line is most important, followed by the second straight FODO extending to 290 m, before the beam enters the Debuncher. From this point on, only a small fraction of muons are produced and no changes to the Debuncher lattice are required for this purpose.



For the AP2 lattice we have considered increasing the number of quadrupoles by factors of 2 to 4, in order to reduce the lattice spacing and beta function. At the moment tripling the number of quads appears like a good compromise and a preliminary lattice design has been made for this case; see Fig. 5, bottom panel. This lattice has been simulated with a full DECAY TURTLE calculation confirming that accepted muon flux is approximately increased 3-fold compared to the existing AP2. More systematic studies including Plan A and B, different lattice spacings, denser lattice in the second AP2 straight section, including wider momentum bins, and others, are currently intensively studied. For instrumenting both straight sections of AP2 with 3 times higher lattice density, 30 additional quadrupoles are required. Fig. 5 was calculated for the examples of 4Q24 quads (pole distance 10 cm, effective length 67 cm), which had been used for BNL g-2 beam line. In the current configuration they would be operated with a moderate pole tip field of ~2.5 kG.

*Debuncher to Muon Ring-*

The large aperture and strong focusing of the Debuncher is ideal for collection and transport of the pion/muon beam. However, the
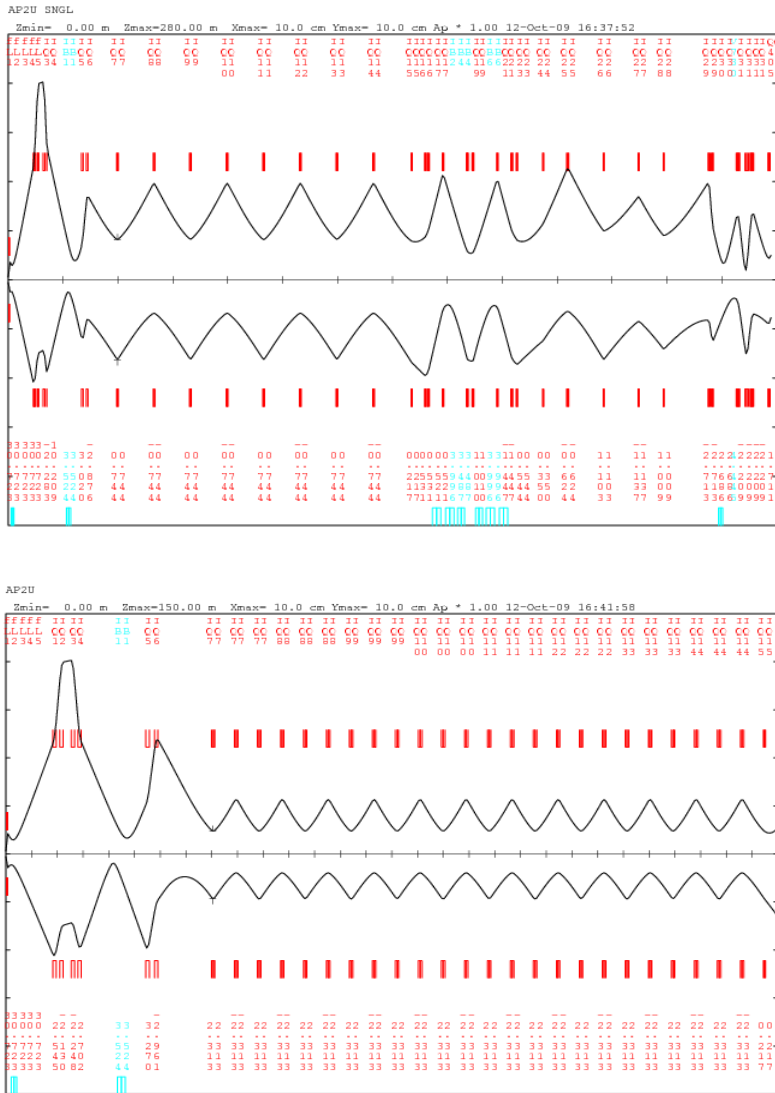
Fig. 5. Beam envelope of present AP3 line (top) and modified AP2 beamline (bottom), with triplet lattice spacing in first straight FODO section. The line depicted in the top panel is the full AP2 280-m long; the bottom panel is the first AP2 FODO up to 150 m. The TRANSPORT display shows the beam envelopes in the y-plane above and the x-plane below the abscissa. The ordinate range corresponds to 10 cm. The schematic layout of the triplet lattice (bottom figure) is for costing purpose. The labels denote beamline elements and pole tip fields in kG.

AP3 line—used today as an antiproton transport line from the Accumulator ring to the Main Injector— has much weaker focusing and hence its admittance is much less than that of the Debuncher. While a further optimization of this beam transport system is forthcoming, for the recent costing exercise the approach taken has been to lay out an AP3 line optics to have the same admittance as the Debuncher ring. This will likely lead to more magnetic elements than necessary for transporting pions/muons from the target, so it gives us an upper bound to the design.

Figure 6 shows the optical layout of the AP3 line used for the costing exercise. What is shown is the square root of the amplitude functions, indicating the relative beam size along the entire length of the line, starting in the Debuncher ring and ending at the entrance to the g-2 ring. The quad spacing of the Debuncher is continued through the beam line essentially until it joins up with the existing AP3 line. At this point, the quad spacing changes, reflecting the use of larger aperture quadrupoles throughout most of the remainder of the transport line. At the very end of the line, the beam is directed over and upward to the g-2 storage ring, and the beam is focused to a waist as it enters the inflector of the ring. The geometry of this beam line is consistent with the geometry of the existing Debuncher ring, AP3 line and the newly designed beam line enclosure leading to the ring as described below.

From this exercise, the total number of quadrupoles is 57, including 14 in the ``stub" region (connecting tunnel to the storage ring). The AP3 line already contains 20 quadrupoles, so the number of new quadrupoles required is approximately 37. A total of 17 dipole magnets are required and already exist in the present line or are available from Fermilab. In the long run, reductions in the number of elements may be possible, where achromatic bend regions might be extended to allow tolerable dispersion waves, bending magnets could be rolled, focusing requirements could be relaxed slightly, as the design evolves.

*Quadrupole Inventory-*

With the increased FODO density in the AP2 line and the beam transport from the Debuncher to the experimental hall outlined above, the current design work yields an upper limit of 67 newly-installed quadrupoles. Fabrication of new magnets would incur a cost of approximately $50k per quadrupole, so an extensive search of magnet inventories at Brookhaven and Fermilab was performed. In the end, a total of 86 quadrupoles with the correct aperture and field gradient were located. In order to make series connections, thus reducing power supply cost, only sets with 4 more identical magnets available were considered. Furthermore, the list of candidates was limited to only shorter magnets weighing <2.5 tons to ease installation in the tight working conditions of the tunnel. Initial conversations with FESS indicate the loading of the tunnel ceiling should not be problematic, although a detailed engineering study of the point loads will be required once the beamline design is fixed. It has been verified with the Brookhaven administration that an MOU will be provided for magnets currently in the muon g-2 beamline, as well as a number of other quadrupoles in the general BNL inventory. Table 2 lists common descriptions and locations for quadrupoles suitable for the beamline modifications required to produce a pion decay channel with high transport efficiency.
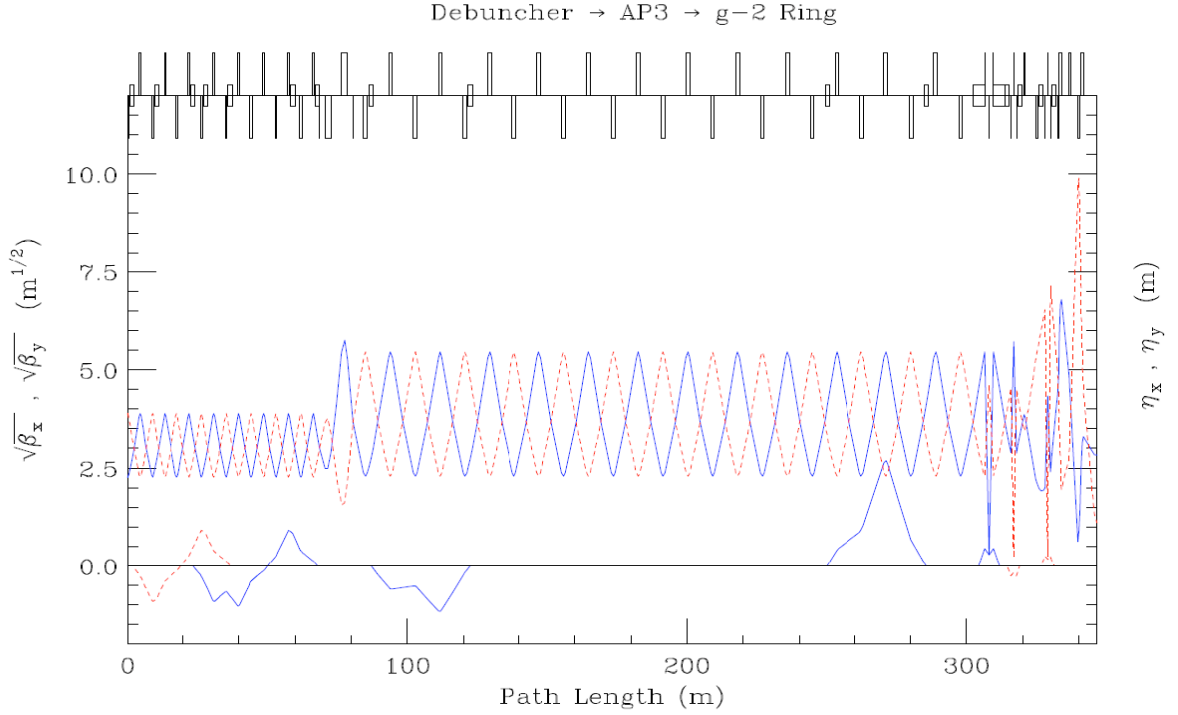
Fig. 6. Layout of AP3 beam line used for costing purposes. The left axis (upper curves) indicates the relative size of the beam envelope and the right axis (lower curves) is the momentum dispersion (orbit spread per $\Delta p / p$).

| Quadrupoles | # Available | Location |
|---|---|---|
| 3Q52 | 21 | Fermilab |
| SQA | 9 | Fermilab |
| SQC | 6 | Fermilab |
| 8Q24 | 13 | Brookhaven |
| N8Q24 | 4 | Brookhaven |
| 4Q24 | 22 | Brookhaven |
| 4Q16 | 11 | Brookhaven |

Table 2. A total of 86 quadrupoles are available from existing inventories, while conservative beamline designs indicate at most 67 will be needed. Of the 50 magnets available from BNL, 27 are currently in the BNL muon g-2 beamline.
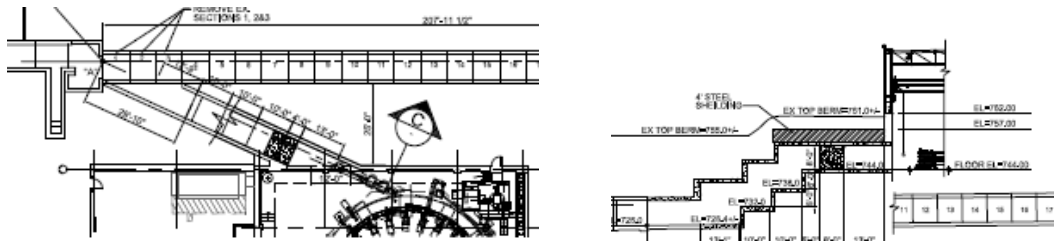
17

Fig. 7. "Beamline Stub" Left: Top view; Right: Elevation view. Beam exits AP2 line through this enclosure and then enters the storage ring.

## Relocating the g-2 storage ring and subsystems

One of the main cost drivers for the experiment is the disassembly, transportation, and reassembly of the ring. This is in large part due to the overall 650 ton weight of the storage ring, the monolithic nature of the large 14-m diameter cryostats, and the labor associated with assembling a device that retains sub-ppm magnetic field uniformity. Details of each phase are given below.

*Disassembly-*

Disassembly of the storage ring requires first removing all of the equipment installed in the gap of the C-shaped magnet including detectors, vacuum components, a system of NMR probes, the storage-ring kickers, infrastructure used for the NMR trolley, and the vacuum chambers. With the various subsystems disconnected, the magnet pole pieces can be removed and the 12 sections of the storage ring yoke can be unbolted. The most technically difficult part of the disassembly is in disconnecting the electrical and cryogenic connections between the three superconducting coils. Each of the three coils is individually contained within an Al cryostat. The connections between the three coils, their interface to power and cryo supplies, and the readout of various transducers is all funneled through a complicated series of inter-connects between the coils. Recent consultation with BNL engineers and technicians involved with the original assembly have confirmed that disassembly is possible and will essentially require a reversal of the original procedure. Luckily, the expertise of the original engineers and technicians is still available for the disassembly. The labor and M&S estimates total $1.3M, and have been slightly increased from the original proposal to include a better estimation of BNL labor rates. A 75% contingency is also added to cover residual uncertainties in the disassembly.

*Transportation-*

Transportation costs are primarily driven by the delivery of the superconducting coils. Since the coils are composed of 14m diameter windings, trucking the coils overland is not possible. Instead, the three coils have to be airlifted to a barge waiting of the Long Island coast, shipped around the St. Lawrence seaway, through the Great Lakes, and up the Calumet-Saganashkee Channel. From a point along the Calumet SAG around Romeoville, IL, the coils can once again be airlifted from the barge to Fermilab. The cost for the airlift of the coils is based on consultation with Erickson Air-Crane. Their Sikorsky S-64 heavy-lift helicopters have a lift capacity of 12.5 tons, more than enough to move the heaviest of the muon g-2 coils at 8 tons. The total cost for the airlift operations has been conservatively estimated at $380k, which is the price assuming the sky-cranes are traveling to New York and Chicago exclusively for the purpose of moving g-2 components.

Since a barge is already needed to move the coils, it is most cost effective to have the 650 tons of steel shipped via the same barge. Based on vendor consultation, the cost of the barge is estimated at $700k with an additional $260k needed for the transportation and craning of the steel to and from the barge at the same time. These estimates are unchanged from the original P-989 proposal, and a 75% contingency has also been added until actual bids have gone out and binding quotes established.

*Reassembly-*

Since the time of the original P-989 proposal, a concentrated effort has gone into better understanding the sequence of steps and labor required to reassemble the storage ring at Fermilab. In coordination with the original Brookhaven engineers and technicians, a 30-point reassembly plan has been developed. This plan is based on the experience of those involved with the original construction, and the detailed WBS documentation that provides a reliable record of the original effort required for assembly. It includes the engineering and technical time to refurbish existing components, assemble and precisely align the storage ring, and reconnect all of the various subsystems. The total construction time, from the moment the high-bay is ready for beneficial occupancy to the time the storage ring magnetic field is ready to be shimmed, is approximately 18 months. During this time it is estimated that about 9.4 FTE years and 4.3 FTE years of engineering will be needed. Additionally, $100k of M&S will be required for lifting fixtures and alignment devices, bring the total cost for reassembly to $2.6M. At this stage, a 50% contingency is additionally applied to the reassembly

## Kicker R&D

The desired uniformity and stability of the magnetic field in the storage ring place strict requirements on the kicker modules needed to kick the muons onto orbit once they are injected into the storage ring. In particular, eddy currents caused by the kicker pulse were required to be below 0.1 ppm within 20 µs of the kick for the E821 experiment. For the new g-2 experiment we would like to decrease the width and increase the amplitude of the kicker pulse to kick a larger fraction of the muons passing through the inflector onto orbit and to further reduce eddy currents in the kicker region.

A prototype straight kicker magnet system exists at BNL. We plan to move the prototype to Fermilab and perform an R&D program to improve the kicker wave form. One of the first tests will be to determine how much the inductance can be decreased by reducing the length of the kicker plates. Further R&D will be performed to demonstrate that the kickers will work at the higher fill repetition rate expected in the Fermilab experiment, which will require an improved cooling system for the pulse-forming network.

## Simulations, Detectors, Electronics, DAQ update

The present design and cost update exercise did not focus on specifics of the "Detector Team" systems; however, continued R&D work has been ongoing as has the development of a full Geant-4 model. The Detector Team plan was reviewed by experts on the Ray Committee, who summarized:

> In the g-2 proposal, the detectors and DAQ were costed at $3M, which included 30% contingency. However, since it was stated that the effort would be funded by "non-DOE" sources, there was very little costing information included. The collaboration responded to our requests for more cost information in a very positive manner, but with the time scale so short, the information still tends to be somewhat sketchy and incomplete. However we have no doubt that the collaboration has the skills and capabilities to build what they claim, given their experience with former versions of the g-2 detector. In what follows we list the various detectors and DAQ components with our best es-

timates (using both the information provided to us by the proponents and some of our own experiences) of the costs and manpower requirements.


We copy the Ray Committee cost summary (Table 3), which we adopt as our working budget.  The Straw system cost is split, with $500k entered in the "DOE-specific" Table because part of this project is being led by Wilson Fellow Casey; the remainder is assumed to be provided by our PNPI collaborators.

| | M&S | Labor | Contingency | Total |
|---|---|---|---|---|
| Calorimeters | $968 | $130 | 30% | $1,427 |
| Position sensitive detector | $237 | $65 | 30% | $393 |
| Straws | $424 | $414 | 30% | $1,089 |
| Waveform digitizers | $608 | $400 | 30% | $1,310 |
| DAQ | $91 | $114 | 30% | $267 |
| **Total Detectors/electronics/DAQ** | **$2,328** | **$1,123** | **30%** | **$4,486** |

Table 3.  Ray Committee estimate for the cost of the detectors, electronics and DAQ.


*Simulation Update-*

Scientists from Boston, Illinois, Kentucky, and Fermilab form the core of our Simulation Team.  We have developed a strong plan to address a number of the open design and optimization issues mentioned in the proposal, from beam transport, to detector design, to computational resources.

To these ends, we are developing a number of Geant-4 models of various systems in parallel.  The Storage Ring model will provide a framework to incorporate all systems beyond the end of the transport beamline.  This includes the storage ring vacuum chambers, the inflector and its cryostat, the kicker and quadrupole plates and supports, and the detector systems.

We currently model all the space and time dependent electric and magnetic fields, including various models of the kicker pulse, the quadrupole scraping scheme, and the storage field fringe region.  Additional functionality is being added at a rapid pace.  We aim for a high-fidelity description of the storage ring systems to enable study of the widest range of phenomena, while maintaining reasonable run time efficiency.

At this stage of the proposal, the primary studies driving development fall into two categories: beam storage into the ring, and detector design. While we have some tools and studies from E821 to guide us, there are many new questions, as well as issues to be addressed in greater detail than was necessary at BNL.

Beam storage studies involve understanding the very sensitive interactions of a number of systems, including the transport beamline, the inflector, various beam obstructions, the kicker system, and the reduction of coherent beam motions.  Early studies with the storage ring model have focused on the positioning and transport properties of the inflector and the details of the magnetic kick.  Ongoing studies are comparing schemes for reduction of coherent beam motions, as well as storage efficiency optimization.

The placement and material properties of the detector systems, particularly those inside the storage ring vacuum, can have a large effect on the stored beam properties and the accuracy of downstream systems.  Muon spin tracking, polarization dependent muon decays, and decay electron tracking are fully incorporated into the storage ring model, so the behavior of particles in the ring can be carefully studied.

Other team members are developing detailed detector subsystem models. We will be studying the effects of various design choices, particularly for the new wire chamber system. In addition, we will study the optimal placement and segmentation of the new calorimeter and hodoscope designs, and develop a model of the scintillating fiber beam position monitors. As these models mature, they will be incorporated into the storage ring framework.

As mentioned, development is currently proceeding at a number of different locations, on a number of different systems. The code portability necessary to achieve this distributed development brings substantial benefits in debugging and code correctness. Portability also protects our development investment, and eases the transition as we move to more and more powerful resources in the future. To date, we have obtained modest development and data storage resources at Fermilab, and porting of the various models to Fermilab computing clusters is planned or under way. Future developments may include the acquisition of substantial data storage resources or migration of code and data storage to a Grid based infrastructure.

*Calorimeter update-*

We continue to design our tungsten-scintillating fiber (W/SciFi) calorimeter default detector system. A full Geant-4 model is running with the correct geometry and we have recently developed a stand-alone scintillating fiber / lightguide model in Geant to track optical photons in order to optimize the lightguide design. We have begun to work with a few sample Geiger-mode APD detectors (also SiPM, etc) in hope that large-area versions might work for the *in situ* readout within the fringe field of the storage ring magnetic field. A new prototype W/SciFi calorimeter is being built. Recently ~$20,000 worth of 0.5-mm diameter fibers ribbons and 0.5-mm-thick tungsten plates have arrived at the University of Illinois and test assemblies are being built. A measurement of the angular distribution of light from these fibers has been made and compared to our Geant simulations. This work is serving as the Senior Thesis for an Illinois student.

*Position-sensitive detector update-*

When working with the Ray Committee, we jointly realized that a simple, scintillator-based Position Sensitive Detector (PSD) would be superior compared to a straw chamber just upstream (out of vacuum) in front of every calorimeter. The PSD would be used for seeds for shower reconstruction and for part of a muon loss monitor (as was done in BNL E821). The University of Virginia has taken on the task of designing this hodoscope system and its assumed SiPM readout. The Ray Committee estimated costs including the scintillator, SiPMs, multihit TDC's, VME crates, and estimates for the remaining ancillary materials.

*In-vacuum straw tracking system-*

The new g-2 experiment plans to make extensive use of tracking detectors placed within the vacuum chamber in front of the calorimeters. The tracking system will be used to perform beam diagnostics, perform systematic studies, calibrate the calorimeter energy scale, and perform a parasitic measurement of the muon electric dipole moment. The Fermilab group is collaborating with the PNPI group on the conceptual design of the in-vacuo straw tracking system. Fermilab is making use of existing infrastructure and expertise from the straw R&D for the CKM experiment, while PNIP is making use of infrastructure and expertise recently used to construct the ATLAS TRT straw system.

*Waveform digitizers-*

As the Ray Committee recognized, our collaboration has had a lot of experiences using the Waveform Digitizer (WFD) approach in a few precision measurements; however, there has been no significant progress or work carried out since the Proposal submission on the design for a new WFD for P-989. We have explored 12-bit chips and have entertained the idea of following the work of Fermilab physicist Paul Rubinov, who has built an attractive, combined-function digitizer with built-in precision voltage control for use with SiPMs.

*Data acquisition update-*

The data acquisition for the new g-2 experiment must handle a raw data rate of 5GB/sec on the frontend processors and handle a derived data rate of ~100 MB/s at the event builder processors and the mass storage. R&D work to design and prototype the acquisition architecture for handling these is now underway. The proposed architecture involves

- the transfer of raw data from waveform digitizers to a frontend processor array over a parallel, high-speed network;
- the processing of raw data into derived T/Q-method datasets by graphical processing units (GPUs);
- the assembly of Q/T method datasets from all calorimeter elements by event-builder processors;
- and the data storage by a tape robot system via a redundant disk array.

Each frontend processor will receive raw data at ~80 MB/s. We've successfully tested the data transfer from either one or two data sources over a 1Gb network through one network card to one frontend processor at up to 128 MB/s with any loss of data packets. These tests are being extended to the larger number of data sources and network cards that is planned for the g-2 setup. Different options such as 1Gb or 10Gb networking, quad-port versus dual-port network cards, and network protocols are being tested.

Each frontend processor will host a GPU for processing the raw data into derived Q/T method data. The raw data will flow from the input network card to the frontend CPU and into the GPU and the derived data will flow from the GPU to the frontend CPU to the output network card. Within the GPUs the incoming data is divided between cores for parallel processing into Q/T method datasets. To date we've conducted tests of CPU/GPU processing speeds and memory transfer rates with a 16-core Quadro NVS 290 graphical processor and a 2.0 GHz Dual Zeon frontend processor with encouraging results. These tests will be extended to a 240 core Tesla C1060 graphical processor and involve more realistic processing of raw data into derived data.

In summary, based on R&D work that taken place, we believe the acquisition architecture outlined in the g-2 proposal is capable of handling the required data rates.

# Summary Tables of Costs (all in k$)

| General Plant Project | Const. / EDIA, Indirect | Cont. | Total | Source |
|---|---|---|---|---|
| g-2 Conventional Facilitie | 5240 | 25% | 6550 | FESS |
| Space management | 450 | | 450 | FESS |
| **Total GPP** | **5690** | **25%** | **7000** | |

Table 4. Building costs from FESS report. Construction (4027), EDIA (886) and Indirects (411) are gathered. Management Reserve is listed on "Cont."

| DOE specific costs | Cost | Cont. | Total | Source |
|---|---|---|---|---|
| New target | 43 | 50% | 64 | Leveling |
| Li lens (costed) or 2 rad-hard quads | 733 | 50% | 1100 | Hurh/Wolff |
| PMAG (pulsed or dc / rad hard) | 425 | 50% | 638 | LevelingWolff |
| Quads in AP2 | 400 | 75% | 700 | Various FNAL |
| Debuncher, AP3 & Beamline stub | 1050 | 75% | 1838 | Various FNAL |
| Radiological issues | 67 | 50% | 100 | Collab Est. |
| Diagnostics | 300 | 50% | 450 | Ray Committee |
| Moving ring | 2780 | 75% | 4865 | BNL engineers |
| Recon ring & maintenance | 3000 | 50% | 4500 | BNL engineers |
| Cryo for g-2 experiment | 1270 | 50% | 1905 | Ray Committee |
| Inflector installation | 504 | 19% | 600 | BNL engineers |
| Kicker modification | 570 | 42% | 809 | BNL engineers |
| Fermilab Straw Detectors | 385 | 30% | 500 | Ray Committee |
| Project management | 2000 | 50% | 3000 | Ray Committee |
| **DOE costs specific to g-2** | **13526** | **55.8%** | **21069** | |

Table 5. DOE-specific costs per narrative in this report. Notes refer to breakdowns of costs.

| Non-DOE costs specific to g-2: | Cost | Cont. | Total | Source |
|---|---|---|---|---|
| Detector/electronics/straws*/DAQ | 3066 | 30% | 3986 | Ray Committee |
| Inflector | 462 | 30% | 600 | Japan quote |
| Field probes | 154 | 30% | 200 | KVI group |
| **Non-DOE costs specific to g-2** | **3682** | **30%** | **4786** | |

Table 6. Non-DOE-specific costs per Ray Committee review (May 2009). $500k has been removed here and placed in the DOE Table as Fermilab's contribution to the straw system.

| g-2 Specific TPC: All sources | Cost | Avg. Cont | Total |
|---|---|---|---|
| Total GPP | 5690 | 25.0% | 7000 |
| DOE costs specific to g-2 | 13526 | 55.8% | 21069 |
| Non-DOE costs specific to g-2 | 3682 | 30.0% | 4786 |
| **Total Project Cost for g-2** | **22898** | **43.5%** | **32854.5** |

Table 7. Total Project Costs rolled up from preceding Tables.

*Notes on DOE-specific cost Table 5-*

| Notes | Costing assumptions and contingencies |
|---|---|
| 1 | New target: M&S (30k); labor (12.8k); Tony Leveling |
| 2 | Option A requires a new lens (100k), transformer (100k); ANSYS tests (100k), pulsed PS and testing program (433); Pat Hurh & Dan Wolff |
| | Option B requires two rad-hard quads (estimate, design, studies not yet made) |
| 3 | Option A requires a new single-turn magnet (75k); its design effort (150k), and a new pulsed PS (200k); Tony Leveling & Dan Wolff |
| 4 | We assume quads are available but require testing and installation. Estimate for placement of a quad is 5k each. We double this for electrical and plumbing considerations, thus 30 quads installed @10K each; We assume 2 new power supplies @50k each. |
| 5 | Here, 65 magnets must be placed (including relocating many already in operation in this line. @10keach; we believe dipoles can be found but budget for 4 new dipoles for the beamline stub at 50k/each; 4 new power supplies are assumed. |
| 6 | Ray Committee estimated 400k based on assumption of a high-radiation area. This is not the case; however, we allow for 100k for general monitors and/or reports needed. |
| 7 | Beamline SWICs and other diagnostic budget planning as recommended by Ray Committee |
| 8 | Moving quotes plus the WBS from the lead engineers and techs who built ring at BNL, adjusted to current Fermilab rates. |
| 9 | BNL engineers detailed plan revisited, +100 k M&S local for tools, lifting jigs, etc. |
| 10 | Klebaner and Theilacker estimate, per Ray Committee. |
| 11 | Specific engineering for installation and testing of a new inflector magnet; BNL engineers. |
| 12 | Work for half-kicker mechanical + additional kickers; BNL engineers. |
| 13 | Added for B. Casey straw system development (partner with PNPI). |
| 14 | Ray Committee recommendation. |

# Timetable

We can envision three areas, which might drive the ultimate schedule as follows:

- The approval / review / funding profile
- The modifications to the proton beam complex and secondary beamlines.
- The conventional construction of the building and reassembly of the storage rin

With appropriate funding, the conventional construction and ring assembly are likely to drive the schedule. If the timing is such that construction of the building can proceed in Oct 2011 when the Tevatron run concludes, then the Table 8 outlines a plan to have the experiment ready for beam at the end of 2014 (or beginning of 2015).

| Task | Duration | Start Date |
|------|----------|------------|
| Preliminary design; prepare project plan and directive | 6 months | July 2010 |
| Start of project; directive signed | 1 month | Jan. 2011 |
| Start engineering; Engineering work starts | 8 months | Feb. 2011 |
| Begin construction; Notice to proceed / purchase order issued | 9 months | Oct 2011 |
| Ring assembly begins | 18 months | June 2012 |
| Magnetic field shimming and measuring begins | 9 months | Dec 2013 |
| Detector equipment installation begins | 3 months | Sept. 2014 |
| Ready for experiment | | Dec. 2014 |

Table 8.  Technically driven schedule based on facility and ring construction.

# Letter from Pier Oddone to Collaboration

**≢ Fermilab**

April 2, 2009

Prof. David Hertzog
Physics Department
University of Illinois
Urbana-Champaign IL 61801

Prof. Lee Roberts
Physics Department
Boston University
Boston MA 02215

Dear David and Lee,

Thank you for the proposal for a New (g-2) Experiment at Fermilab, which we have given the designation P-989, and the presentation at the recent Physics Advisory Committee (PAC) meeting. The PAC appreciated the value of making this "text-book measurement", and was impressed that the experiment could be done for a significantly lower cost than had been thought earlier. The PAC wrote:

*The Committee considered the proposal to improve the high-precision measurement of the muon (g-2) by a factor of four to 0.14 ppm. The muon (g-2) experiments are highly significant due to the accurately calculated value predicted in the standard model (SM), and the sensitivity to a variety of new physics effects at high-mass scales which could result in a deviation from the SM prediction. Although the ultimate limit to the comparison with the SM expectation may be uncertainties in the theory (particularly the light-by-light contribution), the past work at BNL, a tour-de-force demonstration of experimental particle physics technique, was limited primarily by statistics to the 0.54 ppm level (with 0.46 ppm from statistics).*

*In the present proposal, the improvement in precision possible at Fermilab comes mainly from obtaining increased statistical precision due to improvements to the pion capture and transport aspects of the experiment. The versatile Fermilab beam complex would be used parasitically during high-energy neutrino production, and muons will be injected and stored in the muon storage ring relocated from BNL. Data would be acquired within two years of running. In addition, the collaboration proposes to make several substantial reductions in systematic uncertainties.*

*This is an opportune and excellent proposal which is well motivated and represents a technically sound incremental advance over previous work. Realizing the goal would result in an important step forward for fundamental physics measurements, which fits well with Fermilab's other future efforts in precision muon physics at the Intensity Frontier.*

*The Committee recommends that the opportunity presented by this relatively low-cost and high-quality project be pursued. It would be useful to perform an impact and technical evaluation to understand the implications for other aspects of the Fermilab program, and to validate the cost and schedule estimates, which are significantly reduced from what the Particle Physics Project Prioritization Panel (P5) considered. Also, it would be useful to develop mechanisms to draw upon the technical expertise developed at BNL over many years during the previous (g-2) experiment.*

I am happy to have received this encouragement, and congratulate you and your collaborators on the interest in the possibility of a New (g-2) Experiment at Fermilab. We are forming a review committee to evaluate the cost estimate you presented and consider possible conflicts with other parts of the Fermilab program. I trust that we can call upon you and your collaborators to help in this process. We will be in touch about this in the near future.

Again, thank you for your pursuit of making this measurement at Fermilab.

Sincerely,

Piermaria Oddone

cc:

| | | |
|---|---|---|
| Y. Kim | R. Dixon | S. Dawson |
| P. Garbincius | V. White | M. Procario |
| S. Holmes | G. Apollinari | J. Whitmore |
| R. Kephart | C. Hogan | D. Lissauer |
| G. Bock | V. Shiltsev | D. Levy |
| J. Appel | L. Bauerdick | F. Bernthal |