Eleventh International Conference on Magnet Technology, Tsukuba, Japan, 8/28 - 9/1/89

SEP 26 1989

AN ULTRA-PRECISE STORAGE RING FOR THE MUON $g - 2$ MEASUREMENT*[1]

D. Brown, T. DeWinter, E. Hazen, C. Heisey, B. Kerosky, F. Krienen, D. Loomba, E. McIntyre, D. Magaud, W. Meng, J. Miller, L. Posnick, B. Roberts, D. Stassinopoulos, L. Sulak, W. Worstell - Boston University.
 G. Bunce, H. Brown, B. Chertok, G. Cottingham, J. Cullen, G. Danby, J. Jackson, M. May, J. Mills, C. Pai, A. Pendzick, I. Polk, A. Prodell, L. Snydstrup, R. Shutt, K. Woodle - Brookhaven National Laboratory
 K. Becker, M. Lubell - City College of New York.
 T. Kinoshita, Y. Orlov - Cornell University. D. Winn - University of Fairfield.
 K. Jungmann, H. Mundinger, G. zu Putlitz - University of Heidelberg
 K. Endo, H. Hirabayashi, S. Kurokawa, T. Sato, A. Yamamoto - KEK. K. Ishida - Riken.
 W. Lysenko - Los Alamos National Laboratory.
 L. Barkov, B. Khazin, E. Kuraev, and Ya. Shatunov - Institute of Nuclear Physics, Novosibirsk, USSR. J.T. Reidy - University of Mississippi.
 K. Nagamine, K. Nishiyama - University of Tokyo.
 H. Ahn, J. Bailey, P. Cushman, S. Dhawan, A. Disco, F. Farley, V. Hughes, H. Venkataramania, - Yale University.

ABSTRACT

An ultra precise 3 GeV/c storage ring with a 14.5 kG super-ferric magnet is under construction at the Brookhaven AGS for the measurement of the muon anomalous magnetic moment to 0.35 PPM accuracy. This requires a magnetic field which is constant to ≈ 1 PPM and is known sufficiently well that the magnetic field integral averaged over the muon orbits can be calculated to 0.1 PPM. First the magnetic field will be statically shimmed by various techniques. Pole face winding will be used for final small static and dynamic corrections. Very elaborate NMR field monitoring techniques are required. A "movable trolley" located inside the vacuum chamber and the electrostatic focusing quadrupoles will measure the field throughout the muon storage volume. The trolley "siding" is 180° from the injection point where no electric quadrupoles are located. Injection can be interrupted so the trolley can circle the ring. Also ≈ 200 NMR probes located outside the vacuum chamber monitor the field during physics running and control the pole face windings. The very large (≈ 15 m diameter) superconducting coils (SC) are designed. Test winding will soon commence. Orders for the magnet steel can now be placed. R and D on various pulsed and SC dc injection methods is ongoing.

INTRODUCTION

A measurement of the muon $g - 2$ value, i.e. $A \mu = (g - 2)/2$, to 0.35 PPM is a factor of 20 improvement over present knowledge,[1] and is 20% of the theoretical value. This accuracy might

indicate possible deviations from the standard model. The method exploits the spin motion of polarized muons in a storage ring of uniform B.[2][3] The spin precesses with angular frequency ω_s greater than the cyclotron angular frequency ω_c by ω_a , the $g - 2$ precession

*Work performed under the auspices of the U.S. Department of Energy.

MASTER

frequency $\omega_a = \omega_s - \omega_c = e/mc \ A\mu B$. Integral B and ω_a must be measured in the experiment. e/mc is known. To provide vertical focusing, electrostatic quadrupoles are distributed around most of the circumference. For a "magic" momentum of $P\mu = 3.09$ GeV/c, or $\gamma = 29.3$, the effect of the electric field on the precessional frequency drops out[2] requiring "only" producing and measuring a constant B field.

$$\omega_a = \omega_s - \omega_c = \frac{e}{mc} \left[A\mu B - \left(A\mu - \frac{1}{\gamma^2 - 1} \right) \right]$$

$|B \times E|$

Figure 1 shows the layout of the experiment. Longitudinally polarized 3 GeV/c muons are captured in the ring from the decay of injected pions. Alternatively, muons can be directly injected, requiring a fast kicker. Calorimeters distributed around inside the ring detect electrons from muon decay. The electron emission direction is correlated with the muon spin direction, so the muon decay spectrum is modulated by ω_a . Table 1 summarizes this experiment and the previous (CERN) experiment. Table 2 lists parameters of the experiment, Table 3 expected errors. Note that the planned very small statistical error of 0.3 PPM requires knowledge of the field integral to 0.1 PPM.

FIGURE 1 General Arrangement of AGS g - 2 experiment.

TABLE 1

AGS Muon g - 2 Experiment

GENERAL APPROACH - Similar to CERN Experiment

IMPROVEMENTS

1. Primary Proton Beam Intensity (With AGS Booster $\times 100$ to 200). Error, $\omega_a = 0.3$ PPM (CERN = 7.5 PPM)
2. Storage Ring Magnet: Field Homogeneity and Control
Homogeneity (~ 1 PPM) [CERN = 10 - 15 PPM]
Control (~ 0.1 PPM) [CERN = 0.5 PPM]

Achieved by:

- a. Superconducting Coils
- b. Larger Magnet Gap
- c. Aximuthal Symmetry in Iron Construction
- d. Extensive Shimming Features
- e. REX Feedback and Control

3. Magnetic Field Measurement (NMR) - Accuracy (0.1 PPM)

Achieved by:

- a. NMR Trolley, Moveable Within Vacuum Chamber
- b. 200 Fixed NMR Probes Outside Vacuum Chamber
- c. Insertable NMR Probe for Absolute Calibration

4. Detector System - Increased Acceptance, Data Rate Capacity, and Time Measurement Accuracy

TABLE 2

Parameters of AGS Experiment

Pulsed Magnetic Inflector (or dc SC inflector)

π Injection, μ from $\pi - \mu$ decay
 μ Injection, Need fast full aperture kicker

Muon Lifetime, τ (3.094 GeV/c)	64.4 μ s
Orbital Frequency, f_c	6.70 MHz
g - 2 Precession Frequency, f_a	0.229 MHz
Orbit Radius	7112 mm
Central Magnetic Field	1.45 T
Magnet Gap	18 cm
Pole Width	56 cm
Storage Aperture Diameter	9 cm
Electric Quadrupole Field (Pulsed 1 ms)	38.7 kv
Superconductor 1.8 mm $\times$ 3.3 mm NbTi/Cu monolith 1:1 ratio, 1400 SC filaments of 50 μ m.	
Aluminum Extrusion 3.6 mm $\times$ 18 mm with SC Centered, Al/(NbTi + Cu) ratio 10, Al rrr > 2000	
IC = 10,000 Amps, Iop = 5500 Amps (Bop = 2 T)	

Table 1

Counting Rates and Statistical Errors*

Storage Aperture Diameter	90 mm
Protons Per rf Bunch with Booster	4.2×10^{12}
Bunches Ejected per Ring Fill	2
Protons Per Fill	8.4×10^{12}
Pion Ap/p	$\pm 0.6\%$
Pions at Injector Exit Per Fill (1.28×10^7 per 10^{12} protons)	1.07×10^8
Muons Stored Per Fill (at 134 PPM Capture Efficiency)	14×10^{12}
Electrons Counted Above 1.6 GeV Per Fill (20% of the Decays)	2.8×10^3
Fills Per AGS Cycle (1.4 s)	3
Fraction of AGS Protons Used	50%
Fills Per Hour	7714
Electron Counts Per Hour	22×10^6
Total Electron Counts N_e	2.8×10^{10}
Running Time for 0.3 PPM (1 std. dev)	1288 hours
*Pion Injection Case	

Systematic Errors

Source	Comments	Error (PPM)
Magnetic Field	Includes Absolute Calibration of NMR probes and Averaging Over Space, Time, and Muon Distribution	0.1
Electric Field Correction	0.7 PPM Correction	0.03
Pitch Correction	0.4 PPM Correction	0.02
Particle Losses		0.05
Timing Error		0.01
	TOTAL (In Quadrature)	0.12

Figure 2 is a computer printout of the magnet cross section, showing the yoke, the pole, the SC coils, and the flux lines. The C magnet flux return provides access for the calorimeters. The pole base air gap decouples the aperture field shape from the properties of the yoke steel. Standard 1006 low (.06%) carbon steel, can be used for the yoke, the major Fe cost (640 tonnes). Very pure (10005)(.005%) iron pole pieces (the Nippon Steel Company) provide better permeability at high fields, and also expected greater chemical uniformity and freedom from voids. The pole base air gaps will be wedge shaped to correct the large gradient produced by the inside-outside radial asymmetry. The SC coils reduce greatly power supply field ripple and permit larger aperture gaps without the large power dissipation of copper coils. It should be possible to operate continuously for an entire muon run to minimize the effect of hysteresis and eddy currents on the magnetic field

shape. The SC coil pair at larger radius have a common cryostat. The smaller radius coils each have their own cryostat, located well above and below the horizontal mid plane (HMP) to provide access for shimming to the pole base air gaps. At this location the hoop stress on the inner coils is nulled: if located near the HMP a very strong negative hoop stress results.

FIGURE 2 Computed Magnet Cross Section

The ring operates at a single field so extensive static shimming is planned i.e., iron and possibly other magnetizable materials. Improvement of up to 100 times standard magnet tolerances is expected from shimming. A model program is exploring this issue. Changes to the remote iron yoke will produce long "wavelength" changes in the aperture field. An extreme example is the penetrations near the HMP for injection apparatus, cryostat leads, etc. Extra iron will be added near these openings to try to restore the effective total reluctance. Iron shims can also be added or subtracted in the pole base air gaps. This can be used for all wavelengths down to ≈ 10 cm. The sensitivity to iron added is much greater in the air gap than on the surface of the yoke return. This difference can be exploited. In addition, static shimming by adding to or removing material from the pole surfaces provides in principle completely localized control, but with extreme sensitivity. For illustration, a $1 \mu\text{m}$ change in magnet gap changes the field by 5.6 PPM. Area can be exchanged for thickness. For example, a series of small spots covering 1% of the surface but 100 times as thick can be equivalent to the continuous layer. Techniques for accomplishing this are being explored in the model program.

Pole face windings employing economical printed circuits will make the final small corrections. Now simple correcting coils produce higher multipole errors, typically several percent of their desired fundamental. These errors should be less than 0.1 PPM to avoid complicating knowledge of the field, so static shimming is used to the maximum extent to minimize coil excitation. In addition, unless pole face currents are quite small, significant I^2R heating occurs. A 1 PPM dipole correction requires only 0.1 AT per pole.

THE STORAGE RING IRON AND COILS

Figure 3 shows the magnet cross section. The top and bottom blocks will be made of two plates of half thickness welded together. The HMP block will be two separate pieces. This provides a parting surface at the HMP for machining inflector and cryostat penetrations.

FIGURE 3 Magnet Cross Section

The outstanding construction feature of the SC coils is the very large diameter to cross section ratio. Very careful structural design is required. The Al stabilized conductor used is the same as for the Topaz detector solenoid.[3] The 24 turn single layer coils are wound on the inside of the mandrel under outward compression. Hinged supports accommodate the very large differential motions for 14 m diameter SC coils. The

forces (lbs/linear inch) are: outer coil, radially outward 207, vertically 88 away from HMP; inner coil, radially inward 3 and vertically 114 away from HMP. Supercritical helium passing through channels on the mandrels cool to 4.5 K. The cryostat vacuum vessel is anchored to the iron yoke. Eight mechanical stops define a circle concentric with the yoke, with diameter equal to the coil mandrel when cold and powered. The coil is located to ± 0.5 mm. The aperture field is iron dominated so tolerances on current locations are reasonable. Computations show for 1 mm vertical movement of the outer coil at $\rho = 4.5$ cm, a quadrupole of 1.1 PPM, sextupole = 0.2 PPM, others smaller. The dipole change is 56 PPM. Horizontal motion give comparable results. The inner coils are even less sensitive. Unless the coil location is reproducible and constant, field control will be more complicated.

Each pole is attracted to its yoke block by 800 lbs per linear inch. The pole support bolts and hole plugs will be carefully magnetically matched to minimize field errors. The pole edge shims will help smooth any residual effects (Fig. 3). The torque produced by attraction between poles is opposed by pretension in the large yoke tension bolts. All parting surfaces are flat and parallel to $38 \mu\text{m}$. Critical radii are within $127 \mu\text{m}$, as are the 30° sector mating surfaces. Although fabricated in 30° sectors, the ring will be as "continuous" as practical. The sectors fit tightly and the poles overlap the joints to minimize magnetic end effects. Figure 3 shows the iron yoke must be assembled around the double coil cryostat. Poles can be installed (or removed) after all SC coils are assembled. Electronic levels will continuously monitor relative vertical motion to high precision. The support pads will have freedom to accommodate small movement in the horizontal plane, so the ring formed by joining the 30° yoke sectors should maintain its circular integrity.

The magnet design used the computer code "POISSON". Extensive perturbation studies of small changes at the PPM level were made. For simplicity, two dimensional coordinates were normally used plus a simple transformation to the ac-

The air gap behind the poles and the detailed pole shape are used to adjust the field. Figure 4 shows the extreme uniformity computed over the required 4.5 cm radius (≤ 1 PPM). The actual magnet will be much less uniform.

FIGURE 4 Computed Field Uniformity $\Delta B/B_0$ (PPM) in Storage Aperture.

The computer results can be used for perturbative correction following initial measurement. Table 4 shows computed 50 μm changes of the bumps at each pole edge and also the effect of changes in the air gap wedge angle. The wedge produces almost pure quadrupole whereas a quadrupole perturbation using edge bumps produces 41% octupole moment.

TABLE 4

Multipoles Computed at $r = 4.5$ cm for 3 Perturbations

Multipole Moment	I PPM	II PPM	III PPM
(Quad) 1	+ .2	+ 9.2	+ 28.80
(Sext) 2	+ 7.5	0	+ 2.80
3	- 0.1	+ 3.8	0
4	+ 1.4	0	+ 0.10
5	0	+ 0.4	- 0.05
6	+ .1	0	- 0.05
7	0	0	0
8	0	0	- 0.05

Column 1 - All four pole edge bumps - 50 μ m thicker.
Column 2 - Small ρ bumps 50 μ m thinner, large ρ bumps 50 μ m thicker.
Column 3 - Increase pole base air gap wedge by 27 millirads, 20 times fabrication tolerances.

Detailed design remains of the air gap behind the poles. Parallel machined surfaces are preferred over wedges. Preliminary design uses an Al plate with parallel surfaces and with ≈ 20 parallel grooves 2.5 cm wide spaced across the 56 cm plate, in the azimuthal direction. Iron shim stock inserted in the grooves stepwise approximates a wedge to correct the systematic gradient. On the other side of the Al plate, small radial grooves are used for "random" shimming, after measurements. Once the wedge design is complete, final adjustments to the pole shape will be computed using cylindrical coordinates and the final permeability data estimates.

PRECISION SHIMMING AND MEASUREMENT

The ring will probably start at $\Delta R/B_0 > 1 \times 10^{-4}$, ($25 \mu m \approx 100$ PPM). Material variations and geometrical errors are always present. Computer calculations show yoke reluctance changes produce dipole (B_0) only, not significant multipoles. First long and intermediate wavelength variations in B_0 (the central orbit) are reduced by shimming the yoke and air gap behind the poles. Longer wavelength quadrupole and sextupole deviations from computer predictions can also be shimmed out. The pole pieces may or may not be removed once after initial measurements for a major adjustment. All other adjustments should be made in situ. Localized random variations will have to be removed by adding or subtracting material from the air gaps behind the poles or from the pole surfaces. The test magnet is being used to study these shimming techniques, including adding or subtracting from the pole surfaces.

Pole face windings provide the final adjustments. They are also necessary to adjust for environmental or cyclical induced field changes with time. The goal is to produce a field with $\Delta B/B_0 \leq 1$ PPM, including the pole face windings which will be controlled using the very elaborate NMR results. POISSON perturbation calculations will be a great aid in predicting the various correction processes.

NMR permits absolute measurement to 0.1 PPM. The trolley (Fig. 5) will be

used for initial shimming and intermittently during actual data runs. A second long arm will be located at the opposite end of the trolley to that shown. With two probe matrices the restricted region at the injector can be traversed. The probes will probably be oriented in a polar fashion to give multipole fits rather than in the rectangular matrix.

FIGURE 5 Schematic of NMR Trolley.

In addition to the 200 fixed probes outside the vacuum chamber (VC) and the moveable trolley, sets of plunging probes will be inserted into the VC. These absolute calibration probes will check the predictions of the two on-line systems. FM sweeping of the NMR line will be used. This requires no perturbing magnetic fields and uses small sample probes. The small 62 MHz rf transmitters around each probe are shielded. Each synthesizer is multiplexed to 16 NMR probes. NMR data will be collected from one probe at a time. A beam cross section measurement of 25 probes requires 2 seconds. The trolley then moves azimuthally 2 cm, stops, and repeats the process. In about three hours, a complete map with 50,000 points can be taken. Communication to and from the trolley is required and perhaps power for the electronics. Tests have been successful of sliding electrical contacts in vacuum. The trolley rides on tracks in the corners of the VC. The trolley azimuthal drive will either be mechanical or by a motor using the 14.5 kG field. An encoder will monitor the azimuthal location.

All 200 fixed probes will be sampled with a 1 second repetition time. The average NMR error frequency will be fed back to a precision current transformer to control the main power supply. In addition, the probe data will give "regional" information on dipole and

multipole corrections to be performed by localized pole face windings.

An elegant alternate $\int Bdl$ direct measurement is possible. For non-relativistic particles measuring the cyclotron frequency ω_a determines $\int Bdl$ around the ring if their mass is sufficiently well known. At the AGS, $p = 3 \text{ GeV/c Au}^{+1}$ ions with $\beta = 0.15$ could be injected. If the incoming ion beam $\Delta p/p$ is measured to 4×10^{-4} , $\int Bdl$ can be measured to 0.1 PPM.

COMMENT

The pulsed injector used at CERN[2] is difficult and costly to scale up to the desired AGS multipulse cycle. A DC inflector using SC coils is attractive. At least two versions are being pursued. Injector field compensating correction coils will probably be required to permit the 0.1 PPM orbital precision.

Direct muon injection is attractive but requires a fast kicker $\times 90^\circ$ from the inflector. This is being studied.

REFERENCES

1. All the authors either work on this apparatus or will participate in the experiment. Only small portions of this work have been published. Extensive g - 2 Group Reports exist. These are available from the authors listed.
2. Bailey, J. et al., Nucl. Phys. B150, 1 (1979). 1 to 79.
3. Drumm, H. et al., Nucl. Instrum. Methods 158 (1979) 347 to 362.
4. Ikeda, M. et al., Proc. of ICEC-11, Berlin-West (1986) p. 675.

This paper was presented by G. Danby.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.