THE MUON g-2 STORAGE RING MAGNET*

Y.Y. Lee, L. Addessi, Z. Armoza, J. Benante, H.N. Brown, G. Bunce, J.C. Cottingham, J. Cullen, G.T. Danby, J. Geller, H. Hseuh, J.W. Jackson, L. Jia, S. Kochis, D. Koniczny, R. Larsen, M. Mapes, R.E. Meier, W. Meng, W.M. Morse, M. O'Toole, C. Pai, I. Polk, R. Prigl, Y.K. Semertzidis, R. Shutt, L. Snydstrup, A. Soukas, T. Tallerico, F. Toldo, D. Von Lintig, K. Woodle, -- Brookhaven National Laboratory; D.H. Brown, R.M. Carey, W. Earle, E.S. Hazen, F. Krienen, J.P. Miller, J. Ouyang, B.L. Roberts, L.R. Sulak, W.A. Worstell --Boston University; T. Kinoshita, Y. Orlov --Cornell University; D. Winn --Fairfield University; A. Grossmann, K. Jungmann, G. zu Putlitz, P. von Walter --University of Heidelberg; P.T. Debevec, W.J. Deninger, D.W. Hertzog, S. Sedykh, D. Urner --University of Illinois; M.A. Green --Lawrence Berkley Laboratory; U. Haeberlen --Max Planck Institiute fηr Med. Forschung, Heidelberg; P. Cushman, S. Giron, J. Kindem, D. Miller, C. Timmermans, D. Zimmerman --University of Minnesota; V.P. Druzhinin, G.V. Fedotovich, D.N. Grigorev, B.I. Khazin, N. Ryskulov, S.Serednyakov, Yu.M. Shatunov, E. Solodov --Budker Institute of Nuclear Physics, Novosibirsk; K. Endo, H. Hirabayashi, A. Yamamoto –KEK; K. Ishida –Riken; Y. Mizumachi --Science University of Tokyo; S.K. Dhawan, A. Disco, F.J.M. Farley, X. Fei, V.W. Hughes, D. Kawall, M. Grosse-Perdekamp, S.I. Redin--Yale University

Abstract

The muon g-2 experiment at Brookhaven National Laboratory has constructed a 7.112m radius superconducting magnet. The design and construction of the storage ring magnet are described.

1 INTRODUCTION

This article describes the storage ring magnet built for the muon g-2 experiment at the Brookhaven National Laboratory AGS. The goal of the experiment is to measure the anomalous magnetic moment of the mu0.35 parts per million of itself (ppm). The experiment is done similarly to the beautiful CERN experiment [1], with a goal of a factor of 20 greater precision. The technique involves storing 3.094 GeV/c muons in a uniform magnetic field. The energy is selected to be at the "magic gamma", where electric fields can be used to focus and contain the muons in the storage ring without disturbing the measurement of the muon anomaly to first order. The CERN experiment used 40 dipole magnets to form a storage ring 14m in diameter, and the magnetic field was known to 1.5 ppm. The BNL storage ring was built as a single continuous magnet, with the magnetic field to be known to 0.1 ppm. The magnet was designed to be as uniform as possible, both azimuthally and over the storage ring aperture. A very uniform field reduces requirements on the knowledge of the locations of the magnetic field probes, and on the stored muon distribution. Shimming the magnetic field to the required uniformity will be discussed in a future paper; here we present the design, construction details, and operating parameters of the muon storage ring magnet.

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2 MAGNET DESIGN

A 1.451 Tesla magnetic field constrains the 3.094 GeV/c muons to move in a circle with a central orbit radius of 7.112 meters. The storage region itself has a cross sectional diameter of 9 cm. The average magnetic field as seen by the stored muons must be known to 0.1 ppm. Hence, very stringent requirements on B-field homogeneity and stability dominate the design of the ring.

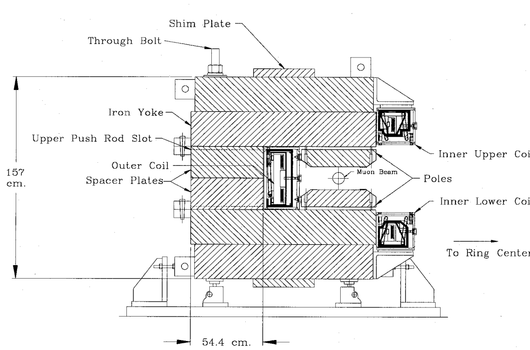

Figure 1: Magnet cross section

The storage ring is built as one continuous superferric magnet, an iron magnet excited by superconducting coils. A cross section of the magnet is shown in Fig 1**.** The magnet is C-shaped as dictated by the experiment requirement that decay electrons be observed inside the ring. The field, and hence its homogeneity and stability are determined dominantly by the geometry, characteristics, and construction tollerances of the iron.

The use of superconducting coils offered the following advantages: thermal stability once cold; relatively low power requirements; low voltage, and hence use of a low voltage power supply; high L/R value and hence low ripple currents; and thermal independence of the coils and the iron. The main disadvantage was that the coils would have a much larger diameter and smaller height than any previously built superconducting magnet.

It is a goal of the experiment to produce a magnet of about 1 ppm uniformity over the muon storage aperture. NMR measurements give the additional factor of 10 improvement in knowledge of the field. The magnet is designed as a shimmable kit. Passive iron shimming is used to correct imperfections in the initial assembly by a factor of two or three orders of magnitude. Iron shimming includes adjustments to the yoke plates above and below the magnet in Fig 1**,** insertion of iron in the air gaps between the poles and yoke (Fig. 2), and adjustment of edge shims on the poles. Correcting coils on the surface of the poles permit ultimate control of static, cyclical, and even slowly varying errors. The surface coils can be used to correct lower multipoles to tens of ppm, so that significant overlap shimming exists between planned iron shimming and the surface coils.

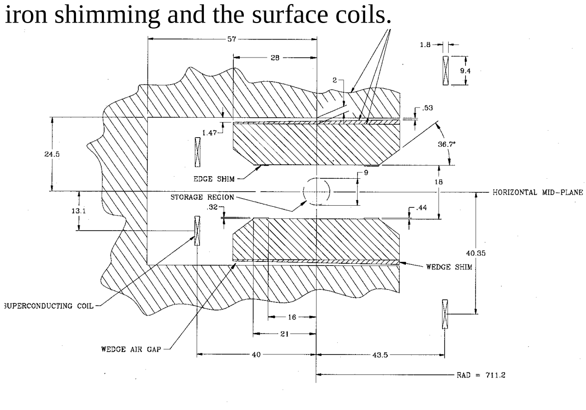

Figure 2: Cross section view of magnet gap region

The air gap between each pole piece and the top and bottom plates, respectively, of the yoke (Fig 2) serves to decouple the storage region precision field shape from the impact of variations within normal tolerances of yoke piece magnetic properties and mechanical dimensions. Thus, the yoke, which makes up the great bulk of the magnet weight and cost, was constructed from conventional quality AISI 1006 (0.07% typical carbon content) iron pieces. Extensive computer field calculations show that expected yoke variations strongly affect the reluctance of the circuit and thus the dipolar field in a given location. However, these variations have very small impact on the field shape. This decoupling of the yoke also desensitizes the impact of major yoke perturbations, principally the large hole for the entering beam and holes in the yoke for the coil transfer lines. Additional steel was added adjacent to these holes to restore the reluctance to its unperturbed value.

Very pure continuous vacuum cast steel is used for the pole pieces. This material is typically "10004" (0.004% carbon content). The higher purity increases permeability at the operating field of the magnet compared to conventional AISI 1006 iron. Even more important is the impact of the purity on inclusions of ferritic or other extraneous material, air bubbles, etc., which are greatly minimized.

A cross section of the azimuthally symmetric pole region is shown in Fig 2. The air gap behind each pole is wedge shaped, with a smaller gap on the inner radius. The wedge compensates for the larger yoke reluctance for field at the inner radius, due to the greater iron path length for those field lines. Pole face iron shims attached near the inner and outer radii are also shown. Three solenoid-shaped superconducting coils with current in series provide the excitation for the magnet.

Calculations of the magnetic field with the two-dimensional POISSON code using rectangular coordinates but corrected approximately to account for the cylindrical magnet were performed. Fig 3 shows the flux pattern. Some calculations were also made with the two-dimensional POISSON code using cylindrical coordinates which confirmed the approximation method. The POISSON model was set up with careful zoning considerations using double precision arithmetic and 5 X 10^{-9} convergence criteria. The outer boundaries were changed with no change in the field shape in the storage region to 1 ppm. Harmonics of the field consistently reproduce the calculated magnetic field to less than 0.2 ppm error at the storage volume boundary of 4.5 cm radius.

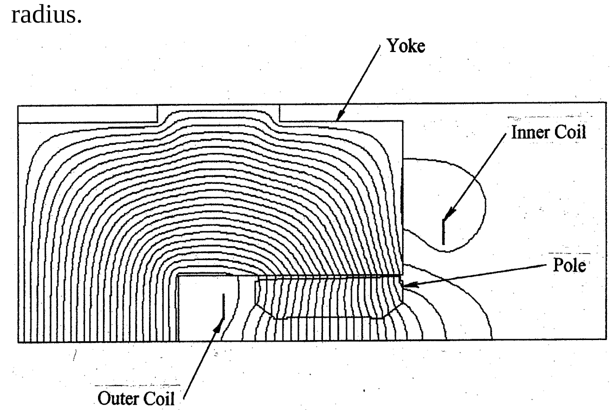

Figure 3: Computed magnetic flux line.

The pole edge-shim location and geometry was varied as well as the pole corner angles beyond these shims. This was done to obtain a reduction in higher moments and potentially a larger volume of good field. The taper angle affects mainly decupole at 10 ppm (at 4.5 cm) and sextupole at 60 ppm, for a 10^{o} change in angle. The pole edge-shims can be used to cancel decupole, so the taper was chosen to give a small sextupole field. The very high precision of computed results is believed to be relevant for perturbations of the final magnet as assembled and measured. Differences between the magnet as constructed and the computed results are expected from, for example, differences in the magnetic reluctance in the actual iron from that assumed in the computation. However, perturbative calculations starting from measured fields are expected to be very accurate.

Magnet parameters are given in Table I

Table I: Magnet parameters.

Design Magnetic Field	1.451T
Design Current	5200A
Equilibrium Orbit Radius	7112mm
Nominal Gap	18cm
Pole air gap	1cm
Pole Width	56cm
Muon storage region diameter	90mm
Inner Coil radius - cold	6677mm
Inner Coil radius - warm	6705mm
Outer Coil radius - cold	7512mm
Outer Coil radius - warm	7543mm
Number of turns	48
Magnet Self Inductance	0.48 H
Stored energy	6.1 MJ
Cold lead resistance	6μΩ
Warm lead resistance	0.1 mΩ
Yoke Height	157cm
Yoke Width	139cm
Iron Mass	682 metric tons
Yoke steel	0.07% C
Pole steel	0.004% C

3. YOKE AND POLE CONSTRUCTION

In this section, the construction of the magnet to achieve desired field quality is described. The superconducting coil windings and the cryogenic system are not described here. The magnet is constructed with twelve 30 degree sectors, to limit the size and weight of the individual parts for ease of fabrication and assembly. The yoke consists of the upper, lower and the spacer plates. Since it is difficult to find suppliers of quality steel who can roll plate steel to the thickness required, these components have been constructed with two separate plates. The plates were welded together at the interface during the machining step. The assemblies are doweled together to maintain their horizontal relationship. A feature of the overall magnetic design is to have the yoke continuous azimuthally. To achieve this, each sector end has four radial projections for bolts to fasten adjacent sector ends to each other. All rolled plate has been completely inspected ultrasonically for voids and the composition of each plate has been determined by chemical analysis The machining requirements of the components were such that as-built vertical yoke gap has an rms deviation of ±90μ, or 500 ppm of the total air gap of 20 cm, and a full width spread of ±200μ. The as-built azimuthal gaps for the lower yoke average 0.8 mm, with an rms deviation of ±0.2 mm. Spacer plates and upper sectors were matched to the lower sectors to equalize the effective azimuthal gap, for the three pieces, weighted by the magnetic reluctance for each sector.

The pole pieces are shown in Figure 1. The poles directly affect the field quality, while the effect of yoke imperfections are minimized by the air gaps between the yoke and poles. The poles require high quality steel, with tight machining tolerances on the flatness of the faces, which define the storage ring gap. The tolerance on flatness was 25μ, which represents 140 ppm of the storage gap. The surface was ground to a 0.8μ finish (4 ppm). The pole widths were machined to 56±0.005 cm, and the thickness to 13.±0.004cm. The upper and lower faces were machined parallel to 0.005 cm. In order to control and adjust the pole location and tilt, the poles were constructed in 10^{o} azimuthal sections, compared to the 30^{o} sectors of the yoke. The pole edges that align with the yoke sectors were machined radial, and the middle pole of each sector was interlocking, with a 7^{o} angle from radial. The poles were located azimuthally with 80μ kapton shims, with the pole edge each 60^{o} in azimuth machined to the correct azimuth. Kapton was used to electrically isolate the poles from each other to control eddy current effects from field changes. The as-built storage ring gap with a design value of 18 cm was measured using capacitance devices to ±1μ accuracy. The gap height varied by ±23μ with a full range of 130μ. The tilts of the poles in the radial direction were measured with a precise bubble level and adjusted to ±50μ rad. The poles were aligned to be horizontal when powered. This required an initial opening angle of 80μ rad toward the ring center to compensate for the asymmetric closing of the gap The shimming gaps between the yoke and poles served three purposes: the gaps decouple the yoke steel from the poles, flat dipole correction coils for each pole were installed in the gaps to adjust the dipole field in azimuth, and the gaps contain iron wedges used to shim the magnetic field. The wedges, sloped radially to provide the C-magnet quadrupole correction, were attached so that they could be adjusted radially. The radial adjustment changes the dipole field locally. The wedges were 9.86 cm wide (azimuthal direction), with 72 per 30^{o} sector. They were 1.65 cm thick on the inner radius, 0.5 cm thick on the outer radius, and were 53 cm long (radial direction). Note that the wedges were rectangular in the r-ϕ plane, so that there was a larger gap azimuthally between the wedges on the outer radius.

The magnet reached the design current of 5200A in June 1996. The shimming and measurement of the field over the storage region will be discussed in later papers.

REFERENCES

[1] J. Bailey et al., Nucl. Phys. B100,1 (1976)