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ULTRAPRECISE MAGNET DESIGN AND SHIMMING*

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Abstract

Computer studies of pole design and magnet shimming techniques are discussed for a very precise 14.72 kG iron core storage ring magnet to be used for the proposed measurement of the muon anomalous magnetic moment. The experiment requires knowledge of the field in the 7m radius storage ring dipole to approximately 0.1 ppm (1×10^{-7}). The goal is to produce field uniformity of approximately 1 ppm. Practical and mathematical limitations prevent obtaining such accuracy directly with a computer code such as POISSON, which is used in this study. However, this precision can be obtained for perturbations of the magnetic field. Results are presented on the internal consistency of the computations and on the reliability of computing perturbations produced by Fe shims. Shimming techniques for very precise field modification and control are presented.

I. Introduction

This report, limited in its scope to computer studies by the authors, discusses a part of the ongoing design effort for an ultraprecise 3 GeV/c storage ring. The g-2 experiment proposal[1] has been approved as part of the future physics program at the high intensity, post-Booster, Alternating Gradient Synchrotron (AGS).

principal error[3] was control of each of the 40 magnet sections by correction coils. These used feedback from a single point NMR measurement in each section. With extra space much more elaborate control can be used.
(ii) A "trolley" capable of moving around the circumference inside the beam aperture carrying a matrix of NMR probes is being constructed. This can be "parked" out of the way without breaking vacuum. This "on-line," albeit intermittently, coexistence of complete mapping and physics running is a new feature.
(iii) The "end effects" of the CERN 40 magnet blocks, although continuous at the pole, contributed significant field and measurement errors between blocks. The new ring will be constructed with 45° sectors machined to be close fitting at their ends to approximate a continuous ring.
(iv) More elaborate use of field shimming by adjustment to the iron cross section remote from the pole faces is planned. A large air gap between the poles and the return yoke will be used as part of this strategy.
(v) Superconducting coils improve B_o stability and reduce the need for magnet cycling. (Power saving.)

The goal of the computer simulations has been to develop techniques to control the dipole field and lower order multipoles so that $\Delta B/B_o < 1 \times 10^{-5}$ over the necessary "good field" 9 cm diameter can be relatively easily obtained. The error would be reduced to $< 1 \times 10^{-6}$ by special local static shimming or active current control such as pole face windings. The final factor of the future physics program at the high intensity, post-Booster, Alternating Gradient Synchrotron (AGS). An international collaboration is involved in detailed design of the storage ring and detection apparatus.

The computer studies are of general interest because of the precision required. Most accelerator magnets perform at a $\Delta B/B_o > 1\times10^{-4}$ field uniformity, for which the computer codes--in this instance POISSON[2] --can, if carefully used, reliably predict the field within the beam aperture. For example, the AGS Booster dipoles agreed with computations to $\Delta B/B \sim 1\times10^{-4}$ over the "good field" aperture. High field superconducting magnets designed by the authors had similar agreement.

The experiment and the storage ring design are solidly based on a highly successful CERN design.[3] The third of a series of muon g-2 experiments, it resulted in a knowledge of the magnetic field integral appropriately averaged over the muon orbits to $\Delta B/B_o$ = 1 to 2×10^{-6}. This, plus other smaller systematic errors were less than the statistical uncertainty of 7 PPM obtained in the experiment. The result stands as the state of the art.

Operation at 5×10^{13} protons in the AGS using the Booster, should permit a statistical uncertainty of 0.3 PPM in the new experiment, assuming the same pion decay injection technique as at CERN. Other injection possibilities might further reduce this error. To carry out this very fundamental measurement, it is desirable that systematic errors be ≤ 0.1 PPM. These are dominated by magnetic field uncertainty, which involves the error in knowledge of the magnetic field, averaged over space and time in relation to the muon distribution. Figure 1 taken from the 1986 update[4] of the proposal shows the general layout of the experiment. Figures 2 and 3 show the magnet cross section.

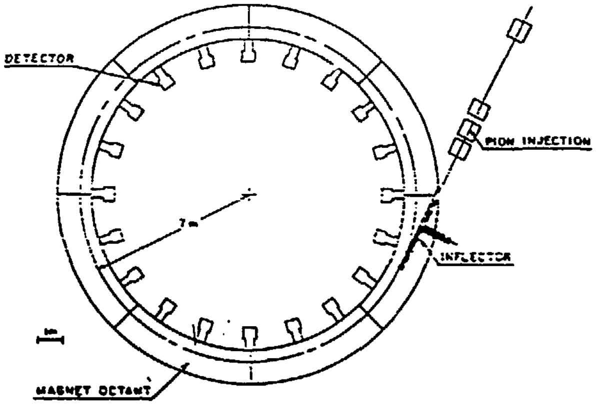
The improvements in precision anticipated for the new experiment come from several areas.

(i) The gap increase from 14 to 18 cm allows more elaborate field monitoring and feedback. For CERN the easily obtained. The error would be reduced to <1x10 by special local static shimming or active current control such as pole face windings. The final factor of 10 to $\Delta B/B_o < 1\times10^{-7}$ would come from measurements, i.e., knowledge of the field adequate to compute the orbits over the muon distribution.

The calculations have already produced a good precision pole profile, although not final. An experimental program will model the polar region in exact scale. Specialty steels will be tested, the impact of inclusions or voids, and grinding or polishing to increase pole surface planarity.

SYSTEMATIC ERRORS

SOURCE	COMMENTS	ERROR (ppm)
Magnetic field	Includes absolute calibration of NMR probes and averaging over space, time, and muon distribution.	0.07
Electric field correction	0.7 ppm correction	0.03
Pitch correction	0.4 ppm correction	0.02
Particle losses		0.05
Timing errors		0.01
TOTAL		0.09



Spin motion -
In a magnetic field B,

$$\omega_s = \frac{eB}{mc\gamma} + \frac{e}{mc} aB;$$

$$\omega_a = \omega_s - \omega_c$$

In a magnetic field B and electric field E

$$\omega_a = \frac{e}{mc}\left[aB + \left(a - \frac{1}{\gamma^2-1}\right)\left|\vec{\beta} \times \vec{E}\right|\right]$$

$$\gamma_{magic} = 29.3, \quad \omega_a = \frac{e}{mc} aB$$

Fig. 1. AGS Muon g-2 Experiment.

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II. Design Optimization

During 1986 the computer calculations were used to reduce the cross section and weight of the magnet to 2/3 that in the Proposal.[1] The use of 1 cm "air" gaps between each pole and return yoke facilitated this, since the flux return reluctance is significantly decoupled from the behavior of the poles. (Table I.)

TABLE I: Multipole Change with Air Gap and Weight Reduction. B = 14.7 kG

	I Base* (W=65cm)	II W=55cm	III W=55cm +4 corners off	IV W=55cm +4 corners off +10 cm off
ΔNI/NI(base)	0	+2.16%	+2.40%	+4.30%
$\Delta B_n/B_o$ (Normalized)				
n=1 (quad)	0	-1.3 PPM	-2.6PPM	-2.6PPM
2 (sext)	0	- .6	- .5	- .7
3	0	- .1	- .1	- .1
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0

Col. I: the 1985 Proposal Magnet Cross Section, with 1 cm air gap behind each pole.

Col. II: for a 10 cm (18%) reduction in width of the return yoke block, centered on the horizontal midplane.

Col. III: also cut four corners off magnet.

Col. IV: also reduced thickness of top and bottom yoke member by 10 cm. (This increased reluctance by ~2%.)

In all cases in this Report, multipoles are expressed at R = 4.5 cm, y = 0; B_o = 14.7 kG.

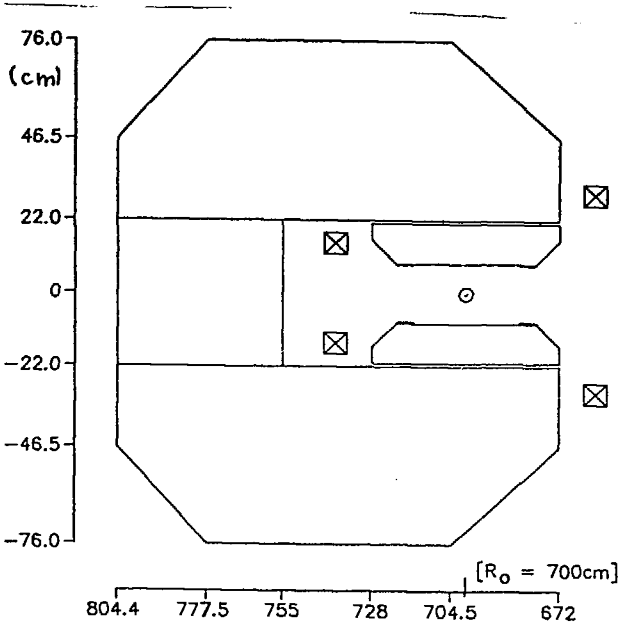

Fig. 2. Magnet cross section.

The C-magnet return produces a very large systematic gradient. Three perturbations have been explored: (i) tilt the pole faces, (ii) larger bumps on the inside pole edges than on the outside, (iii) shim in the air gap at the rear of the poles to induce more flux on the inside. While (i) and (ii) are possible for refined shimming, they are too local to the "good field" aperture and generate significant octupole. Method (iii) can give a large almost pure quadrupole so the magnet can start off with the systematic C-magnet gradient removed. See Table III.

TABLE III. Perturbing Air Gap Behind Pole to Remove Quadrupole.

ΔB /B	I "Standard"	II Pole gap	III Effect of

at R = 4.5 cm, y = 0; B_o = 14.7 kG.

The result of very large weight (and cost) reduction is an appreciable increase in reluctance and ampere turns requirement, but no significant change in multipole field errors. The magnetic and dimensional tolerances of the yoke flux return are not unusually tight and are relevant mainly to the dipolar term. For example, scaling from Col. II, a 0.65mm change in width of the HMP block would produce dipolar change of 1.4 x 10^{-4}: equivalent to a 25 µm change in the 18cm gap.

Consider the effect of raising the central field by 1% in two cases, the geometry of Col. I and of the Col. IV in Table I. This result is shown in Table II.

TABLE II: Change for B_o increased by 1% to 14.847 kG.

	I (Base, 1985)	II (light weight)
ΔNI/NI (base)	1% + 0.16%	1% + 0.58%
$\Delta B_n/B_o$ (4.5 cm)		
n = 1 (quad)	-14.2 PPM	-14.7 PPM
n = 2 (sext)	-6.6	- 6.8
n = 3	- .2	- 0.2
n = 4	- .3	- 0.3
n = 5	0	0
n = 6	0	0
n = 7	0	0
n = 8	0	0

Note the effect on the multipoles of raising B_o by 1% is almost independent of the very large changes in yoke geometry. The quadrupole is due to C-magnet yoke asymetry. The 1% higher field reduces the permeability in the vicinity of the air gaps. The reduced permeability in the poles also effects the sextupole. Table II can also be used to establish tolerances on magnetization properties in the pole steel. A 1% change in saturation magnetization would produce roughly the change in Table II. The storage ring central field will always operate at 14.72 kG.

$\Delta B_n/B_o$ (4.5 cm)	I "Standard" Case	II Pole gap Slope ±0.40 cm	III Effect of "wedge" gap
n=1(quad)	-204.6 PPM	+ 3.4 PPM	+208 PPM
n=2(sext)	- 38.9	-32.8	+ 6.1
3	+ 1.7	- 1.1	- 2.8
4	- 0.2	- 0.5	- 0.3
5	+ 0.2	+ 0.2	0
6	- 1.3	- 1.3	0
7	- 0.2	- 0.2	0
8	- 0.2	- 0.2	0

Col. I: standard case (see Fig. 2) 1 cm air gap.
Col. II: base of pole wedged so that air gap varies from 1.4 cm at R = +28 cm to 0.6 cm at R = -28 cm. This effect can be accomplished also by moving the center of gravity of shims in the parallel air gap.
Col. III is the difference between II and I.

Note the almost pure quadrupole, with only 1% octupole contribution. Because of the very large radial asymetry being corrected, a small sextupole change occurs in the baseline gradient corrected magnet.

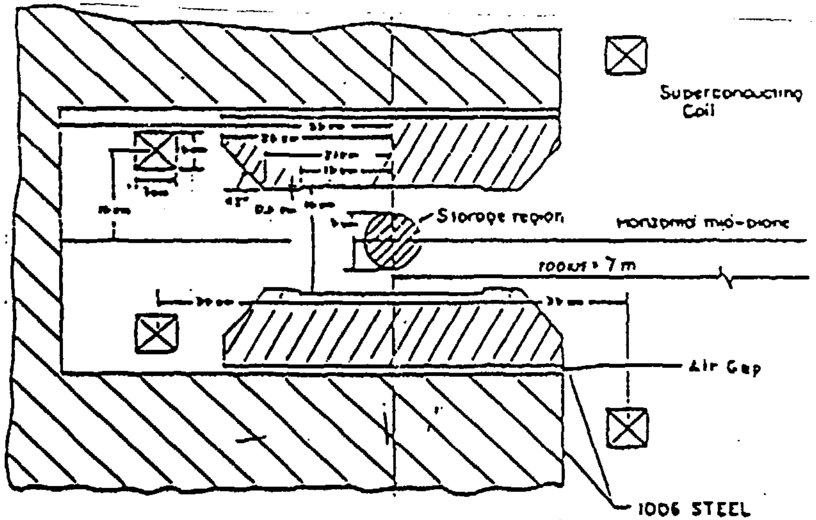

Fig. 3. Magnet Polar Region.

The effect of the coil motion is shown in Table IV.

TABLE IV: Coil Position Tolerance

n	Multipole (4.5 cm)	Outer Coil Up 1 mm.	Outer Coil Inward 1 mm.
0	Dipole	- 24.1 PPM	+ 7.56 PPM
1	Quadrupole	+ 0.60	+ 0.38
2	Sextupole	- 0.09	- 0.12
3	Octupole	+ 0.02	+ 0.04
4	Decapole	- 0.01	- 0.02

Notes:

1. Outer coils are located at R=739 cm, y=±15 cm (Fig. 2 and Fig. 3.)
2. Inner coil not tabulated but sensitivity less.
3. All multipole terms < 1 PPM, except for dipole.

III. Shimming Perturbations

The approach of the g-2 design is to produce pole surfaces as flat as economically practical by machining plus possibly grinding or polishing the surface of sections to minimize "hill and dale" errors. Very homogeneous material will be used to minimize "pot holes."

For reference, consider simplified 0.001" (25 μm) errors in the gap and the parallelity of the pole surfaces: (i) a .001" systematic gap error gives 141 PPM dipole change, (ii) a .001" side-to-side tilt gives a quadruple of 11 PPM at R = 4.5 cm, (iii) a .001 symmetric variation: the gap at the center .001" different than at the pole edges, gives ~ 3.6 PPM sextupole. These illustrate the incentive to make the dipole $\Delta B / B_0$ very small around the azimuth by shimming the reluctance or possibly by current loops remote from the pole surfaces. The present state of the design is shown in Col. II of Table III. A slight change to the symmetric pole profile will remove the 33 PPM sextupole. Touchup of radial asymmetry can take care of quadrupole and octupole in the computed magnet. The

Table V permits estimating .001" (25 μm) rms bumps height errors: 2 PPM sextupole and 2 PPM quadrupole occur, with everything else smaller. Skew moments (not computed) with be comparable. Three tests are used for the internal consistency of the computations. The magnetic fields as computed and the magnetic multipole fit agree in the 9 cm "good field" region to 1 PPM (See Fig. 4.) Next, a change in the geometry of an iron portion of the magnet is made and the difference in the multipole content computed. The amplitude of this change is varied. A linear relationship for the multipole content of the change is observed for reasonable perturbations lending itself to extrapolation. Finally the computed field is tested based on symmetries. An iron bump is added to one of the four corners of the poles and the change computed. By symmetry, the multipoles resulting from this perturbation will also be produced by similar bumps in the other 3 quadrants, with predictable phase changes. This permits prediction of any combination of up to 4 bumps. The computations confirm the prediction for modest size perturbations. Note this process involves generation of the mesh for each geometry, iterative calculation of the field everywhere in the iron and air, and generation of the field multipoles.

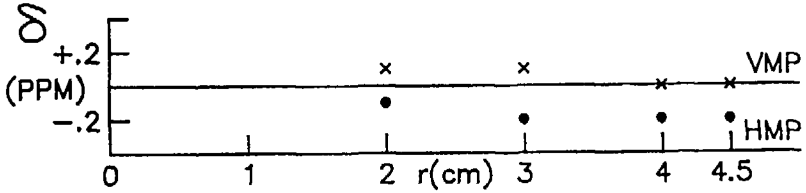

Fig. 4. Difference δ=Field-Multipole Reconstruction.

The computations need only be credible to perform *perturbations* at the PPM level, i.e. to predict the necessymmetric pole profile will remove the 33 PPM sextupole. Touchup of radial asymmetry can take care of quadrupole and octupole in the computed magnet. The perturbation studies at this sensitivity illustrate techniques for optimization: the magnet as first constructed will have larger errors.

Next to the pole faces themselves, the most sensitive perturbations are the bumps on the edges of the pole fences. In the present design these are 0.5 cm thick and 6 cm wide, starting at R = ± 15 cm. Their tolerances and their utility for perturbations are shown in Table V.

TABLE V. Perturbation of Bumps on Pole Face Edges.

B_n/B_o (4.5)cm	I Add .02 cm to inner bumps	II Add .02 cm to outer bumps	III Predicted Sum	IV Computed Sum
n=1(quad)	+18.0	-18.4	- 0.4	+ 0.7
2(sext)	+14.9	+15.1	+30.0	+30.1
3(oct)	+ 7.9	- 7.7	+ 0.2	+ 0.1
4	+ 2.9	- 2.9	5.8	5.8
5	+ 0.8	+ 0.8	0	0
	+ 0.2	+ 0.2	+ 0.4	+ 0.4

In Col. I and II, the field has been computed for the thickness of the two bumps increased at the inner and outer radius respectively. Col. III is the analytic sum of I and II. Col. IV is the computed sum.

Note that Col. IV shows symmetric perturbation and gives only symmetric terms. The ratio of 10 pole to sextupole is 20%. This bump perturbation should be used in combination with more remote perturbation to suppress both sextupole and (n=4) 10 pole simultaneously. Col. I and II show that if equal and opposite sign changes (I-II) were made on the inside and outside radius, the sextupole would not change, only quadrupole and other odd terms. This is a good way to reduce octupole, with residual gradient done by other means.

The computations need only be credible to perform perturbations at the PPM level, i.e. to predict the necessary correction for the residual error measured in the magnet. The magnet will have both cylindrically symmetric and azimuthally varying field errors due to geometrical factors, magnetic forces, magnetization in iron, temperature control, etc. (Note that 1 PPM≡0.18 μm gap tolerance.) Careful operating control plus shimming perturbations can correct anything except the most local pole surface defects. A fundamental limit is the temporal stability and reproducibility of the magnet. Active feedback must be used beyond this limit. Dynamic and possibly also static corrections will be made with current loops applied in sections, possibly 1 meter long. Such coil corrections are analytically straightforward to compute, but should be small at least on pole surfaces. In addition to taking space and generating heat coils have "lumpy" current distributions which generate higher multipole errors as they correct. This will impact on the final < 0.1 PPM knowledge of the field.

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