EDDY CURRENTS INDUCED IN A MUON STORAGE RING VACUUM CHAMBER DUE TO A FAST KICKER*

W.Q. Feng, Physics Department, Nanjing University, Nanjing, China
E.B. Forsyth, AGS Department, Brookhaven National Laboratory, Upton, New York 11973 USA

Abstract

The goal of AGS E821 is a precision measurement of the muon magnetic moment (g-2) value to 0.35 ppm. A problem with muon injection is the effect of the residual magnetic field during the measurement period due to the eddy currents in the vacuum chamber induced by the kicker pulse. The paper presents a mainly analytical look at the nature of the eddy currents as an equivalent RL circuit and describes a method to solve 2D Maxwell's operations under pulse excitation with some quantitative estimates of the decay time constants. Analysis of the results show that the field due to eddy currents is dependent on the chamber dimensions, type of material, and duration of pulse rise, flattop and fall. The field created by the rising edge of the waveform is largely cancelled by the falling edge, providing the pulse is short compared to the diffusion time of the eddy current. The simulation results agree with the theoretical analysis and confirm the residual integral field at the start of the measurement period is acceptable.

I. INTRODUCTION

A new experiment is being built at Brookhaven National Laboratory to measure the g-2 value of the muon to a precision of 0.35: an improvement of a factor of 20 over the best available data. The ultrahigh precision aimed for at BNL presents unusual challenges in physics and in technology. Muon injection plays an important role in achieving the precision of 0.35 ppm, because direct muon injection into the storage ring is more efficient in producing stored muons, and the hadronic background associated with many pions interacting with storage ring material is absent. Direct muon injection into the storage ring is accomplished by giving the muon beam a 10 milliradian kick at a quarter of a betatron wavelength from the inflector. The disadvantage of direct muon injection is that one has to deal with the effect of the residual magnetic field of the fast kicker due to eddy currents in the vacuum chamber.

The method of attack is to derive LR circuits for the eddy currents and to solve 2D Maxwell's equation with pulse excitation, thus obtaining a group of solutions of the eddy current magnetic field, eddy currents and decay time constants [1]. Some computer simulations are given of eddy currents induced by a fast kicker. The simulation results agree with the theoretical analysis and confirm the residual integral field at the start of the measurement period is acceptable.

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II. SOLUTION OF THE DIFFUSION EQUATION

In Fig. 1, if l >> w and h >> d, then the two-dimensional kicker magnetic field in the chamber wall, parallel to the wall can be considered.

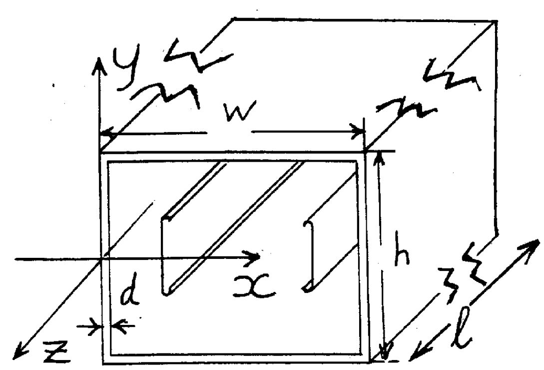

Fig. 1. Vacuum chamber with two-plate kicker.

In this situation, $\frac{\partial \vec{D}}{\partial t} \ll \sigma \vec{E}$ and Maxwell's equations are:

$$\nabla\ x\ \vec{E} = -\mu \frac{\partial \vec{H}}{\partial t}, \qquad \nabla x \vec{H} = \partial \vec{E} \qquad \text{(1a), (1b)}$$

where $\mu = \mu_o \mu_r$ is the magnetic permeability, and σ is the electrical conductivity. Applying boundary conditions we obtain the diffusion equations for the special situation:

$$\frac{\partial^2 Ez}{\partial x^2} = \sigma\mu \frac{\partial E_z}{\partial t}, \qquad \frac{\partial^2 Hy}{\partial x^2} = \sigma\mu \frac{\partial Hy}{\partial t} \qquad \text{(2a), (2b)}$$

An iterative form of solution has been examined [2], assuming the fast kicker produces a exponential step pulse. In the beginning of the iteration, the magnetic field $H_o(t)$ is uniform over the cross section of the chamber wall; this field is perturbed by the eddy currents. The decay times

Table 1
Time Constant L_n/R_n

$L_n(t)/R_n(t)$ (µS)							
$\sigma[10^6(\Omega.m)^{-1}]$	d (mm)	n = 1	n = 2	n = 3	n = 4	n = 5	n = 6
38.2 (Al)	3	10.9	2.74	1.22	0.68	0.44	0.11
38.2 (Al)	5	30.4	7.60	3.38	1.90	1.22	0.30
38.2 (Al)	10	122	30.4	13.5	7.60	4.86	1.22
1.11 (S.S.)	3	0.32	0.08	0.035	0.02	0.013	0.0032
1.11 (S.S.)	5	0.88	0.22	0.098	0.055	0.035	0.0088
1.11 (S.S.)	10	3.53	0.88	0.39	0.22	0.14	0.035

have been calculated, represent in Fig. 2 by $L_n(t)/R_n(t)$, quantitative results are given in Table 1.

Typical time constant for the decay in aluminum is ~ 500 µs. In practice the excitation waveform of the kicker has both a rising and falling edge with a width that is much less than L_1/R_1. The net effect due to the difference between positive and negative eddy currents will produce residual magnetic field which could affect the accuracy in determining the overall field integral around the storage ring. Calculation shows the next field decays much more quickly than for a unidirectional pulse due to the cancellation effect: a short pulse is required relative to the diffusion times. The rise and fall times can be optimized to keep the eddy current field to a minimum.

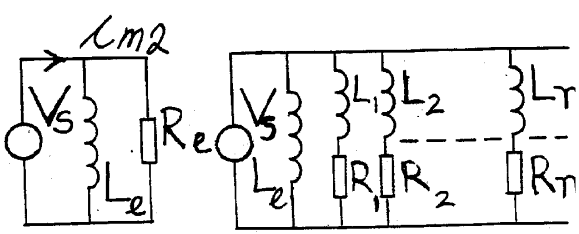

Fig. 2. Eddy current equivalent circuits.

III. COMPUTER SIMULATION

The required high precision implies the integrated residual field $R\int_o^{\theta_1} B_e d\theta$ should become less than 1 part in 10^7 of the integrated main dipole magnetic field $R\int_o^{2\pi} B_o d\theta$ on the mid-plane at the start of the measurement (~ 10 µs), where B_e is the eddy current field, B_o is main dipole field, θ is the angle subtended to the center of the ring, θ_1 is the angle occupied by the fast kicker, and R is the radius of the storage ring.

For the magnetic kicker, using an underdamped sine waveform the eddy current field/main field is < 1 x 10^{-7} if t_r < 100 ns. The eddy current field at beam centerline using the program PE2D with a waveform assumed to have 60 ns The vacuum chamber material is 2020 aluminum. Table 2 lists the eddy current contribution to $\int_o^{\theta_1} B_e d\theta$ as a function of time after injection for a stripline kicker (E & H field deflection). The time dependent diffusion of eddy currents is clearly seen: there is a rapid change immediately after the end of the kicker excitation pulse which slows as time increases.

IV. CONCLUSIONS

The analysis has served to emphasize the following important points:

(1) The field due to eddy currents is dependent on the chamber dimensions, type of material and times of rise, flat-top and fall of the excitation pulse.

(2) The eddy current field has a fast transient component and a steady state component.

(3) The cancellation of the field produced by the rising edge of the excitation wave form is largely produced by the falling edge, providing the flat-top portion is brief.

(4) Numerical computations indicate the residual integral field due eddy currents to eddy currents at the start of the measurement period will be < 1 part in 10^7 of the main bending force for a fast kicker with an optimized excitation waveform.

Table 2
Ratio of Kicker Field
Deflection to Main Field Deflection

Time, ns	Ratio, pts in 10^6	Comments
65	0.92×10^3	Half the total deflection of 11 mrad comes from the H field
165	1.3	End of kicker deflecting pulse
1020	0.43	-
5020	0.18	-
20,000	0.10	-

ACKNOWLEDGEMENT

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