THE INJECTION KICKER SYSTEM FOR THE MUON G-2 EXPERIMENT[1]

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Abstract

The muon g-2 experiment is designed to measure the anomalous magnetic moment of the muon to an accuracy of 0.35 ppm by measuring the difference between the spin precession frequency and the cyclotron frequency of the particle in a known magnetic field. The injection kicker is designed to deflect 3.094 GeV/c muons by an angle of 10 mrad into a storage ring with a radius of 7.112 m. No magnetic materials can be used in or near the beam line because of the high precision with which the field of the main dipole magnets must be known. Eddy currents induced in the vacuum chamber by the fast kicker pulse, and their effect on the main dipole field must also be considered. An air core magnet which is driven by an underdamped capacitor discharge modulator using a spark gap switch has been designed. This design, as well as test data, will be presented.

I. INTRODUCTION

The muon g-2 experiment utilizes a superconducting storage ring of 7.112 m diameter. The injection kicker magnet is required to deflect muons of momentum 3.094 GeV/c by an angle of 10 mrad. The kicker system including the power modulator, charging power supply, magnet, beam chamber, and main ring dipole magnet are shown in Figure 1. The kicker system consist of three one m long air core magnet with an aperture of 80 mm vertical by 100 mm horizontal. A crossectional view of this magnet is shown in Figure 2. This magnet is driven by an underdamped capacitor discharge circuit with peak amplitude of 6500 A, and resonant frequency of approximately 11 Mrad/s. The power modulator switch is a 100 kV spark gap. The entire discharge circuit is in a coaxial housing, and is shown in Figure 3.

Several unique restrictions which apply to this kicker system are the result of the kicker magnet being inside of the main ring dipole magnet beam pipe. No magnetic materials can be used in or near the beam pipe because of the high precision which the dipole field must be known. The high vacuum, and radiation, in the beam pipe limits the use of plastics for electrical insulators, and mechanical supports. Both the charging waveform, and discharge pulse must be carefully analyzed to insure that any eddy current fields induced in the beam vacuum chamber quickly decay [1].

II. THE KICKER MAGNET

Three different types of kicker systems where investigated to meet the above requirements. They were, an electrostatic kicker, a transmission line kicker and a magnetic kicker. The basic pulsed power parameters for each of these types of kickers are, ±400 kV pulse for the electrostatic kicker, ±200 kV and 4000 A pulse for the transmission line kicker, and < 100 kV and 6000A pulse for the magnetic kicker. Placement of the kicker magnet in the main magnet beam chamber has serious consequences for each of these types of kickers. The limited space inside the chamber precludes the electrostatic and transmission line types of kickers due to electric field stresses. The magnetic kicker induces eddy currents in the vacuum chamber which must not contribute to the main dipole field by more than 0.1 ppm, or 21 mG. Thus, considerable effort was taken to study the effects of eddy currents in the beam chamber

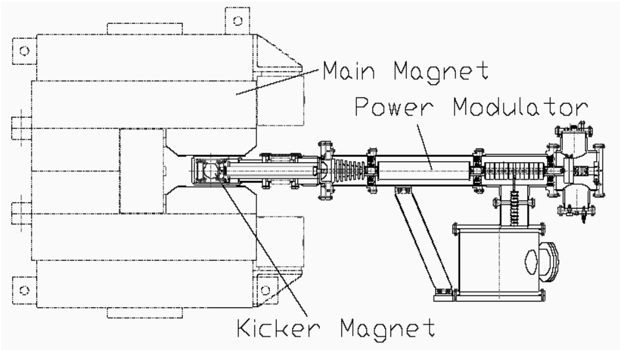

Figure 1. G-2 experiment main dipole magnet, vacuum vessel, kicker magnet and modulator.

The magnet for the g-2 muon storage ring injection kicker consists of two titanium strips of 80 mm height separated by 100 mm. The kicker system uses three magnets of 1 meter length each. The transient eddy current analysis code OPERA 2D/TR was used to investigate field distribution, eddy currents, magnetic gain, energy losses and inductance for this magnet. The drive current for the magnet was assumed to be a damped sinusoid,

$$i = i_o e^{-\alpha t} \sin \omega t$$

because of the simplicity of producing such a waveform for an inductive load. The length of the vacuum chamber, l, is much longer than either the width w or the height h, which in turn are each much larger than the thickness d of the chamber walls. Thus, it is possible to consider the two dimensional field

$$H_o(t)=H_o^{-\propto t} \sin wt.$$

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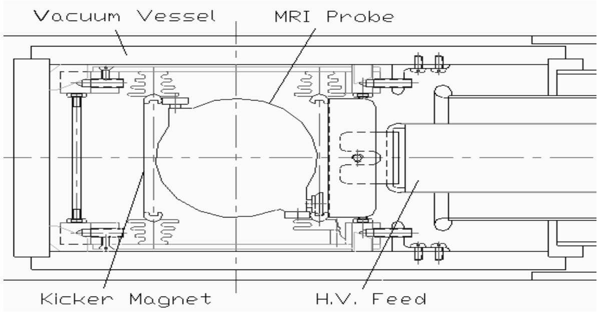

Figure 2. Kicker magnet and vacuum Figum vessel, with field mapping NMR probe shown.

Since the displacement currents can be ignored, Maxwell's equations reduce to

$$\frac{\delta E_z}{\delta x} = -\mu \frac{\delta H_y}{\delta t}$$

$$\frac{\delta H_y}{\delta x} = \sigma E_2 \quad ,$$

and the diffusion equations are

$$\frac{\delta E_z}{\delta x^2} = \sigma\mu \frac{\delta E_z}{\delta t}$$

$$\frac{\delta^2 H_y}{\delta x^2} = \sigma\mu \frac{\delta H_y}{\delta t} \quad ,$$

where $\mu=\mu_o\mu_r$, and σ is the conductivity. The eddy currents in the vacuum chamber walls have been investigated for this type of driving waveform using an iterative approach and solving the diffusion equations.

The conclusions drawn from this analysis are:

1. The vacuum chamber material should have a μ_r=1, low conductivity and be as thin as possible for the eddy current fields to decay quickly.
2. Decreasing the thickness improves the decay of the steady state eddy current.
3. Increasing α improves the decay of the steady eddy current, but also requires more drive current because of the reduction of the kicker field. To gain a compromise between the eddy current residual field the kicker magnet field, and the current pulse width, ω should be increased with α.

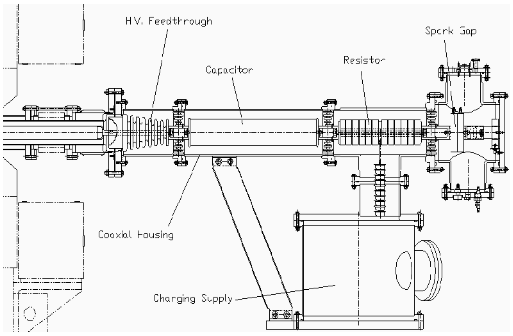

Figure 3. Power modulator, high voltage feedthroughs, and charging supply.

Computer simulation wiring PE2DITR and OPRA2OITR were used to show that appropriate choice of dimensions, shapes, and materials for the vacuum chamber, and driving waveform could result in the residual eddy current field contributing less than 1 in 10^7 to the main dipole field at the start of the measurement period. This analysis was performed with several different waveshapes, and it was found that both undershoot of the pulse and parasitic oscillations helped to reduce the effects of induced eddy currents. In particular, the eddy current field induced by an underdamped current pulse with an 80 ns rise time and high frequency parasitic oscillation decays to 12 mG after 10 µs.

Other kicker magnet parameters calculated were an inductance of 0.21 µH/m, magnetic gain of 0.025 G/A, and a field uniformity of ΔB/B(0,0)=25 %.

III. THE POWER MODULATOR

The pulsed power modulator to drive the above magnet is the underdamped capacitor discharge circuit shown schematically in Figure 4. The spark gap used is a Maxwell Laboratories model 40264 gap, triggered with a Maxwell Laboratories model 40168 trigger unit. The charging supply is a command resonant supply which uses the leakage inductance of the 85:1 step up transformer to charge the 10 nF discharge capacitor. A charge current pulse for the charging system is shown in Figure 5. Because the charge current flows through the magnet, eddy currents induced by this pulse where also analyzed. Their contribution to the main dipole field was not significant however, because of the relatively low frequency, amplitude and long decay time for the pulse.

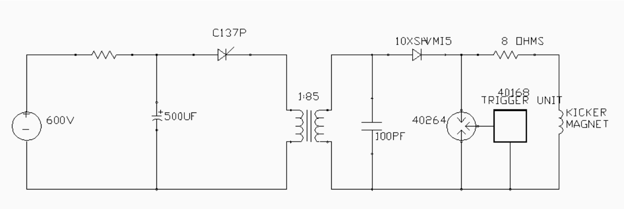

Figure 4. Schematic of power modulator and charging supply

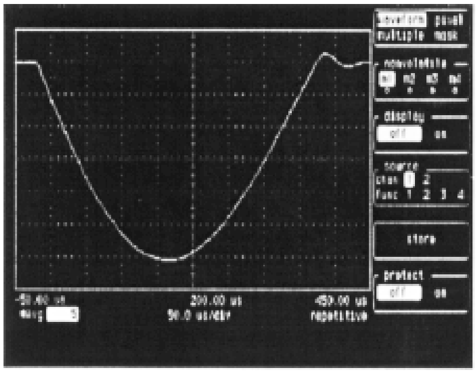

Figure 5. Charging current, time base is 50µs/div, amplitude is 50 A/div.

A typical discharge pulse is shown in Figure 6. One of the main concerns about the discharge circuit was the choice of a switch to use. The primary objective was to minimize circuit inductance. Thyratons were considered, but a tube to block up to 100 kV would be a three gap tube, and tube inductance would be on the order of several hundred nano Henries. Multigap tubes where also problematic because of the capacitive coupling between gaps as they break down. The tight eddy current requirements discussed above could be exceeded by gap coupled prepulses. Spark gap switches have inductance of less than 50 nH in one gap up to 100 kV, but suffer from high jitter and short life. The lifetime for the G-2 experiment is not critical, however the jitter must be kept to less than 5 ns. With this in mind jitter measurements where made on the Maxwell gap and trigger unit. Figure 7 shows the gap jitter as a function of gap voltage and pressure. Figure 8 shows the trigger generator jitter as a function of output switch air flow and pressure.

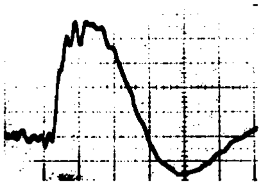

Figure 6. Modulator Output Pulse. Time base is 100 ns/div, amplitude is 1000 A/div.

From this data it is clear that jitter of less than 5 ns can be obtained by the Maxwell trigger generator and gap if proper gas pressure and flow are maintained.

IV. CONCLUSIONS

Eddy current fields induced by the fast kicker pulse and the slower charge pulse will decay quickly enough so as not to distort the main dipole field for the g-2 experiment by a factor of greater than 1 in 10^7. Jitter measurements have been made on the spark gap switch and trigger unit., and show that the jitter requirement can be met with careful control of the gap and trigger gap pressure and air flow. A second gap from English Electric Valve is being investigated. This gap offers several advantages over the Maxwell gap, however, it has not been tested. The EEV gap is sealed and requires no synthetic air, regulators, and air flow controls, and is triggerable from an EEV provided pulse transformer whose driving voltage is only several hundred volts on the primary. A prototype modulator magnet and vacuum vessel have been designed and are now in fabrication. The primary area of concern now is the insulators supporting the kicker magnet. These insulators are now being tested for high voltage breakdown.

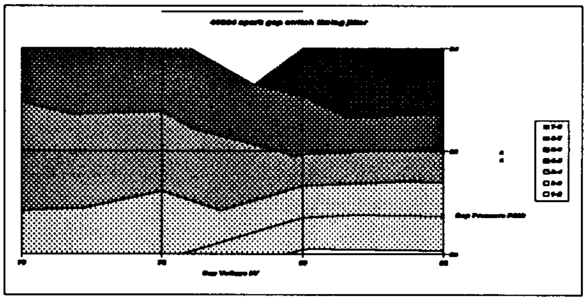

Figure 7. Spark gap jitter in nano-seconds as a function of gap voltage and pressure.

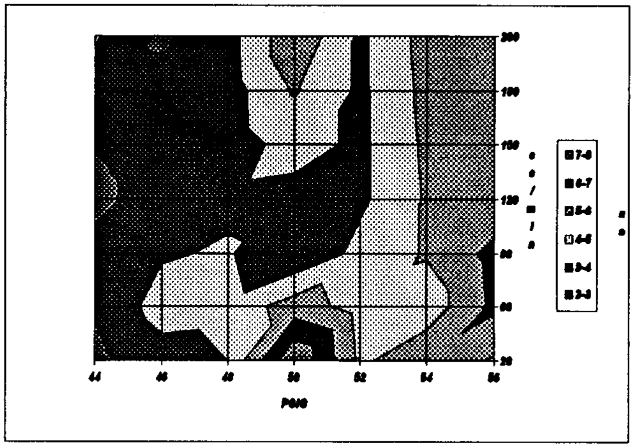

Figure 8. Trigger generator jitter in nano-seconds as a function of pressure and flow.

V. REFERENCES

[1] W.Q. Feng, and E.B. Forsyth, “Eddy Currents Induced in a Muon Storage Ring Vacuum Chamber Due to a Fast Kicker”, ibid.

VI. ACKNOWLEDGEMENT

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