ELECTRIC AND MAGNETIC DESIGN OF THE g-2 MAGNETIC KICKER[1]

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Abstract

The ultra-high precision g-2 experiment requires a fast kicker to deflect incoming muon beam with a momentum of 3.094 Gev/c. A magnetic kicker was selected since this approach requires the lowest excitation voltage of all designs considered. However, a higher driving current (>6000A) is required which leads to more residual eddy current field to influence the main dipole magnetic field. Several possible magnetic kicker designs were investigated to determine their effects on kicker field quality, driving efficiency (B/I) and inductance per unit length. A satisfatory construction is a two plate kicker with shaped edges for the two electrodes. Using the transient eddy current analyses (Opera 2d/TR)[1], the authors studied a variety of factors which affect the eddy current residual field. This paper presents the electric and magnetic parameters of the magnetic kicker which was completed in 1996 and has been put into operation now.

1 INTRODUCTION

The g-2 experiment which is being readied to run at the Brookhaven National Laboratory Alternating Synchrotron will attempt a measurement of the anomalous magnetic moment of the muon to an unprecedented accuracy[2][3]. Muon injection needs a fast kicker which deflects incoming particles with a momentum of 3.094 Gev/c, into their proper equilibrium orbit. A kick of 10 mrad is provided by a kicker located 90° of betatron phase angle from the inflector. The fast kicker magnetic field has the potential to create eddy currents which decay very slowly[4][5] in the surrounding vacuum chamber wall and other adjacent conductors in the vacuum chamber. In view of the high precision (<1 ppm) necessary for the main dipole integrated field it is very important to consider carefully the residual field of the eddy currents at the start of the measurement period(~10μs) after injection is completed. High voltage insulation is another important factor in the design.

There are three kinds of kickers available:

- Electro Static Kicker(ESK) which deflects the muon beam mainly with an electric field at very high voltage (±400kV)[6].
- Transmission Line Kicker (TLK) - with both electric and magnetic fields at medium high voltage (±200kV) and current (~4000A)[7].
- Magnetic Kicker (MK) - with a magnetic field at lower voltage (<100kV) and higher current (>6000A).

It is possible with exiting technology to develop all the proposed kicker system. The MK seems the simplest and cheapest because of lower high voltage (including pulser), but the eddy current residual field is a crucial problem in the MK design. The electric and magnetic design includes proper selection of the shape, size and spacing of the kicker structure, and a feasible driving waveform for the MK. These aspects are the subject of this paper.

2 SHAPE AND STRUCTURE OF MK

Consideration of the injected beam orbit indicates that the integrated field is ~0.1 Tm, and at the start of the measurement period (~10μs) the integrated residual field should decrease to less than 1 part of 10^7 of the integrated main dipole magnetic field (~64 Tm). The principle requirements for the MK as a function of kicker length l, are shown in table 1.

Table 1
The principle requirements for MK

1(m)	B_k(G)	B_e(mG)
3	>330	<21
4	>250	<16
5	>200	<13

B_k is kicker field and B_e is the eddy current field at the start of the measurement period. It is clear that less driving current is needed if a longer MK is used and less residual field can be tolerated.

In general, the kicker magnetic field has to be created without the use of any magnetic material enhancement, i.e. the field has to be created in air, or in this case vacuum.

There are two kinds of simple MK structures available: four-rod conductors (1 or 2 turns) and two plates (1 turn). Using the transient eddy current analysis (Opera 2d/TR), the field distribution, eddy currents, driving efficiency (B/I), energy loss and inductance per unit length were studied for different shapes and structures, different driving current waveforms and different times.

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Two conclusions have been obtained:

- The homogeneity $\Delta B_y / B_y(0,0)$ and harmonics ΔS for the two-plate kicker are much better than for the four-rod kicker.
- The two-plate kicker has less inductance and slightly larger transfer function $B_y(0,0)/I$ than the four-rod kicker. This means the two-plate kicker needs a lower voltage to achieve the required $B_y(0,0)$. Furthermore, properly shaping the edges of the two electrodes for the two-plate kicker has the advantage of improving the homogeneity and increases $B_y(0,0)/I$.

3 EDDY CURRENT

Eddy current have two negative consequences: power loss and eddy current stray field. The eddy current stray field has two pernicious effects, first is to decrease the kicker field during the kick period, second is to maintain a residual field for a long period after the kick action. For the g-2 experiment, this means that measurements cannot begin until the field diminishes to the permitted value, hence a loss of data. A number of computational runs using Opera 2d/TR indicate that the decrease of the kicker field amounts to approximately 10-15% due to eddy current demagnetization. In order to compensate for this effect the driving current must be increased. The residual field is a more complicated problem because it directly affects the measurement accuracy. Because the field due to eddy currents depends on the chamber geometry, the type of material of the chamber and electrodes, and times of rise, flat top and fall of the driving current, the contribution of each factor will be discussed separately.

3.1 Driving current

Eddy current computations[6][7] studied three different driving functions, of which two - exponentially rising (falling) rectangular function and trapezoidal function - gave satisfactory results for the residual field. Unfortunately, engineering analysis and computer simulations using the program Microcap IV[8] confirm that the design of a high voltage pulser for either of these types of waveform would be very difficult for the magnetic kicker. A damped sine waveform is simpler to generate when driving an inductive load. Analysis of beam tracking in the storage ring shows that some undershoot is desirable [9], therefore the circuit should be slightly underdamped.

Theoretical analysis indicates that the falling edge of the excitation waveform largely cancels out the eddy current field produced by the rising edge of the excitation waveform, provided the flat top is brief. The net effect due to the difference between positive and negative direction eddy currents will result in a residual magnetic field which could affect the accuracy in determining the overall $\int Bdl$ around the storage ring. Thus the pulser circuit should generate a waveform which has as short rising and falling edges as possible. Computer modeling of an underdamped capacitor discharge circuit showed that a 6000 A, 80 ns rise time current pulse into the two plate magnet would need an initial charge of approximately 85kV, which is a reasonable voltage for the vacuum chamber geometry.

Using transient analyses for different driving current waveforms,, including three critically damped waveforms and three underdamped waveforms(~20% undershoot) with different rising and falling edge, the eddy current field B_e at t=10 μs are quite different. Several general conclusions can be reached:

- The faster the rising edge, the more quickly the eddy current residual field decays.
- Underdamping with an undershoot is helpful for decreasing the residual field. Fig.1 is a driving current waveform that is optimized to meet all constrains.
- Parasitic oscillation on the driving waveform, which is a common effect, has no effect on B_e because the frequency of the parasitic oscillation is quite high.

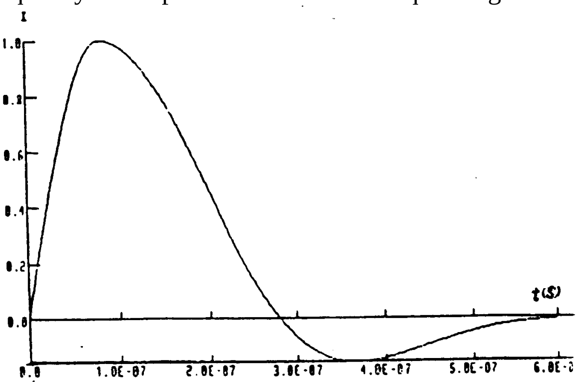

Fig.1 A optimized driving current waveform

3.2 Dimensions

The eddy current residual field not only depends on "time", including the measurement time and the driving waveform, but also depends on "space", which means the size and shape of the vacuum chamber, electrodes and other conductors in the vacuum chamber, and the relative location of the measurement point.

A two-dimension model of the electrodes and vacuum chamber used for analysis is shown in Fig.2. The actual structure of the muon vacuum chamber is significantly more complicated. The vacuum chamber is made of 24 sections, each of which widens in the longitudinal direction to accommodate the trajectory of the decay electrons. A detector which measures the difference between the electron spin precession frequency and the cyclotron frequency, or the g-2 precession frequency, is

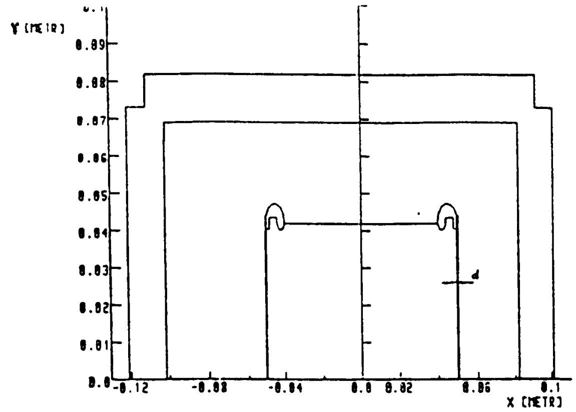

Fig.2 2D Model of MK

located at the end of each section. The electrical and magnetic parameters change when the inside size of the chamber tapers from the narrowest (x = 0.082 m as in Fig. 2) to the widest (x = 0.279 m). Obviously, there are different magnetic parameters for these extreme sizes, even if the same driving waveform (Fig.1), the same maximum driving current amplitude I_m=6472A, and the same electrodes were assumed. Thus a good approximation for a two-dimensional model can be achieved using average values.

It is clear that there are different parameters for different electrode thicknesses. Simulations show that it is acceptable to select d=0.508 mm because decreasing d would result in more B_e, and increasing d could cause more energy losses of the incident electrons produced by the muon decay, i.e. a loss of data, but would not further improve the eddy current residual field.

3.3 Material

The main factors for selecting materials to be used for the vacuum chamber, electrodes, supports, feedthroughs and so on, include mechanical , electromagnetics, and particle-physics. It is desirable to make the vacuum chamber from aluminum, but titanium is more suitable for the electrodes in order to decrease the residual eddy current field in the vacuum chamber and minimize high-voltage breakdown effects.

The requirements of the storage ring prohibit the use of magnetic materials in or near the beam chamber as this would affect the mapping of the main dipole field. Magnetic flux density B_y, inductance L, power loss P, homogeneity and harmonics are all a function of time, because eddy currents change with the variation of the driving current. In addition, the losses depend on the driving current and eddy currents, but the driving current is the primary loss. The magnetic flux density mainly depends on the driving current.

4 HIGH VOLTAGE

The simulations (Electro 2D Field Analysis[10]) show that the electric field stress maximum $|E|_{max}$ along the kicker electrode is just under 15 kV/mm at an electrode voltage of 70 kV. Thus electric stress is not a insurmountable problem because the mean breakdown stress for large gaps in vacua is around 27kV/mm[11]. A very smooth, polished surface for all electrodes and other conductors in the vacuum chamber (including the chamber) is very important and the feedthroughs need to be carefully designed. Computer simulations give the kicker capacitance (per unit length) ~30pf/m. When considering the standoffs, supports and feedthroughs, the capacitance is not well-distributed and will be vary in the longitudinal direction depending on the material used.

5 CONCLUSION

Important design considerations include:

- To approximately optimize the dimensions, shapes, and materials of the vacuum chamber, electrodes, supports and feedthroughs, so as to satisfy the many requirements.
- To experimentally regulate the driving current waveform to get an acceptable residual field and measure it at the start of measurement period.
- To minimize the connection inductance between the pulser and MK because the total magnetic kicker inductance is quite small (less than 1.8μH).

6 ACKNOWLEDGMENT

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