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Magnetic Field in a Prototype Kicker Magnet for the KAON Factory

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Abstract—Kicker magnets are required for all ring-to-ring transfers in the 5 rings of the proposed KAON factory. The kick must rise from 1% to 99% of full strength during the time interval of gaps (80 ns to 160 ns) created in the beam so that beam extraction losses are minimized. The "kick" strength must have a uniformity of ± 1% over the useful aperture of the magnet. PE2D calculations have been performed to determine the uniformity of the combined electric and magnetic kick in the aperture of a TRIUMF prototype kicker magnet. Measurements of the magnetic field were performed with 50Ω striplines while the prototype magnet was excited with a low voltage 1 MHz sine wave. The predicted and measured results for the magnetic field in the prototype kicker magnet are in good agreement, and are presented in this paper. Circuit analysis code PSpice has been utilized to mathematically model the magnet and stripline probe, and the results of the simulations have provided a better understanding of the effect of parasitics upon the measurements.

I. INTRODUCTION

The kicker magnet parameters for the 5 accelerator rings in the KAON Factory are described in [1] and [2]. The kick must rise from 1% to 99% of full strength during the time interval of gaps (80 ns to 160 ns) created in the beam so that beam extraction losses are minimized. The uniformity and stability of the kick strength are individually required to meet tolerances of ± 1% so that the beam emittance is not increased significantly by the field.

As part of the KAON Factory project definition study a prototype transmission line kicker magnet was built at TRIUMF [1]. The TRIUMF kicker magnet design is based on the design of those of CERN PS division [3]. The prototype kicker is a 10 cell magnet with a design characteristic impedance (Z_0) of 30Ω. Equivalent circuit parameters for each cell have been derived from measurements with the kicker magnet driven by a pulse. The magnetic and electric field distribution in the prototype magnet has been determined by PE2D [4] studies. The magnetic field uniformity was measured with a 50Ω stripline probe while the magnet was excited with a 1 MHz sine wave.

II. THEORETICAL MEASUREMENT SIGNAL

A. Magnetically Induced Signal

Consider an ideal transmission-line type kicker magnet of length ℓ, driven through impedance R_{in}, and terminated at the output with impedance R_{out}. Let the launched voltage at the input to the kicker magnet be a sine wave of amplitude V_0 and frequency $\frac{\omega}{2\pi}$. The instantaneous launched voltage (V) at the input of the magnet (position $x = -\ell$) is given by:

$$V = V_0 e^{j\omega(t - \frac{x}{\ell}\tau)} \tag{1}$$

where t is time, and τ is the fill time of the magnet.

It can be shown that the steady-state voltage across the kicker magnet $[\Delta V(t)]$ is given by, $\Delta V(t) =$

$$V_{ssi} e^{j\omega(t+\tau)} \left(1 - \frac{(R_{in} + Z_a)}{Z_a} \frac{R_{out} e^{-j\omega\tau}}{(R_{in} + R_{out})}\right) \tag{2}$$

Where, $V_{ssi} e^{j\omega(t+\tau)}$ is the steady-state voltage at the input to the magnet. Z_a is the apparent impedance looking into the input of an ideal transmission line kicker, which is terminated at its output with R_{out}. Z_a is given by [5]:

$$Z_a = Z_0 \left(\frac{R_{out} + jZ_0 \tan(\omega\tau)}{jR_{out} \tan(\omega\tau) + Z_0}\right) \tag{3}$$

The relationship between V_o and V_{ssi} is given by:

$$V_o = V_{ssi} \left(\frac{Z_0(R_{in} + Z_a)}{Z_a(R_{in} + Z_0)}\right) \tag{4}$$

From Faradays' Law, the magnetic field in the magnet aperture is given by the integral, with respect to time, of the voltage across the magnet. If a stripline probe of length ℓ and width d is inserted into the magnet aperture, of width W, then the signal induced on the probe $[V_m(t)]$ is given by:

$$V_m(t) = \frac{d}{W} \Delta V(t) \tag{5}$$

Equation 5 neglects the finite delay of the stripline and assumes that there is no fringe fields outside of the magnet aperture. For small values of $\omega\tau$, and when $R_{in} = R_{out} = Z_0$, (5) can be rewritten such that the amplitude of the magnetically induced signal (V_m) is given by:

$$V_m = \omega\tau V_{ssi} \frac{d}{W} \tag{6}$$

B. Parasitic Capacitance

Parasitic capacitance between the high voltage conductor of the kicker magnet and the stripline probe results in a displacement current which can significantly modify the magnitude of the measured signal. For a kicker magnet which is terminated with a matched impedance, and neglecting the delay of the stripline probe, it can be shown that the measured signal $[V_s(t)]$ is given approximately by:

$$V_s(t) = \frac{R_{sc} V_o e^{j\omega t} \left(1 - e^{-j\omega\tau}\right)}{R_1 + R_{tm} + R_2 + R_{sc}} \left(\frac{d}{W} - \frac{C_{hp} R_v}{\tau}\right) \tag{7}$$

Where C_{hp} is the parasitic capacitance between the high voltage conductor and stripline probe: R_{sc} is the input impedance to the oscilloscope; R_1 is the sum of the parasitic resistance of the ground conductor of the stripline probe and the ground conductor of the coaxial cable to the oscilloscope; R_{tm} is the value of the resistance used to terminate the remote end of the stripline probe; R_2 is the sum of the parasitic resistance of the signal conductor of the stripline probe and the center conductor of the coaxial cable to the oscilloscope. $R_v = R_1$ if the signal stripline of the probe is towards the high voltage conductor, and $R_v = -(R_1 + R_{tm})$ if the ground stripline of the probe is towards the high voltage conductor.

The effect of the capacitance term $\left(\frac{C_{kg}R_v}{\tau}\right)$ in (7) can be significantly reduced by averaging the results of two measurements. The first measurement is performed with the magnet driven from one end (input) and terminated at the other end (output), and the second measurement is carried out with the order of magnet input and output reversed (see section IV). The average of the magnitude of the signals, with the magnet driven from each end, is given approximately by:

$$V_m = \left| \frac{R_{sc}\left(1 - e^{-j\omega\tau}\right)}{R_1 + R_{tm} + R_2 + R_{sc}} \left(\frac{V_o d}{W}\right) \right| \tag{8}$$

C. *Ferrite Losses*

It is desirable to carry out the measurements on the kicker magnet at as high a frequency as practical since, for an ideal kicker magnet, the magnitude of the signal induced in the stripline probe is proportional to frequency [see (6)]. However the kicker magnet is not ideal: each cell has a finite cut-off frequency, and the ferrite exhibits losses.

The ferrite losses can significantly reduce the instantaneous voltage drop across the kicker magnet, and hence the magnitude of the signal induced magnetically onto the stripline probe. The losses associated with each cell may be represented by a resistor (R_P) in parallel with the self-inductance of the cell. For the purposes of analytically determining the effect of ferrite losses upon the magnetically induced signal it is assumed that, for relatively small values of $\omega\tau$, it is permissible to approximate the kicker magnet as a single lumped inductor of value L_t in parallel with a single lumped resistor of value R_{Pt}. It can be shown that the magnitude of the magnetically induced signal is given approximately by:

$$V_m = \frac{d}{W}\omega L_t \kappa V_{ssi} \sqrt{\left(\frac{1 + \frac{1}{Q^2}}{\omega^2 L_t^2 + R_e^2}\right)} \tag{9}$$

Where $R_e = \left(R_{out} + \frac{R_{out}}{Q^2} + \frac{\omega L}{Q}\right)$, and κ is a scaling-factor which depends upon the length and position of the stripline probe ($0 \leq \kappa \leq 1$). $\kappa = 1$ if fringe fields at the two ends of the kicker magnet are included.

R_{Pt} can be estimated from $R_{Pt} = \omega L_t Q$, where Q is the Quality factor of inductor L_t. If the ferrite is assumed to be lossless ($Q = \infty$), then $R_e = R_{out}$, and V_m approaches $\frac{d}{W}\omega L_t \kappa V_{ssi}\sqrt{\left(\frac{1}{\omega^2 L_t^2 + R_{out}^2}\right)}$

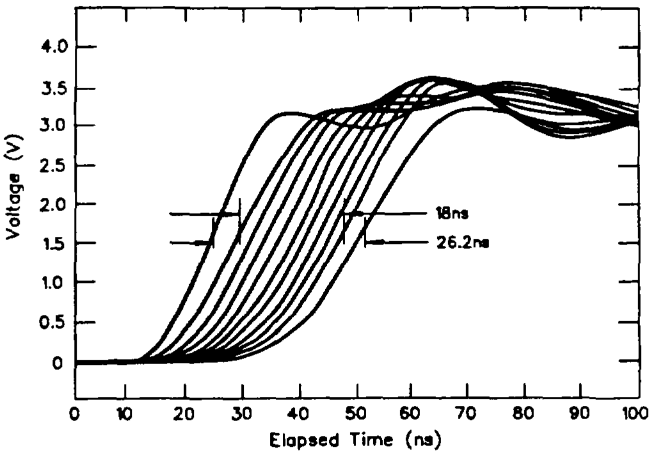

Fig. 1: Propagation of a pulse through the prototype kicker magnet

III. MEASUREMENTS

A. *Pulse Excitation: Magnet Parameters*

In order to determine the capacitance and self inductance per cell of the prototype kicker magnet, the magnet has been driven with a voltage pulse. Fig. 1 shows the propagation of a voltage pulse, with a 20ns rise time, through each of the 10 cells of the kicker magnet. A high impedance low-capacitance voltage probe was used for measuring voltage on each of the high-voltage capacitor plates. The kicker magnet was driven from a 30.0Ω source and terminated with a 30.0Ω resistor for this measurement.

The 'flat-top' oscillations in Fig. 1 are damped out in an elapsed time of approximately 200 ns. The dimensions of the ferrite of a cell are chosen so that the field in the ferrite is below the knee of its B-H curve. In addition the reluctance of the magnetic-circuit of a cell is dominated by the reluctance of the aperture, hence the self-inductance is virtually constant up to the maximum operating current. The self-inductance of a cell was determined by the following procedure:

- Calculate the flux by integrating, with respect to time, the difference in voltage of the two high voltage capacitor plates which sandwich the ferrite of the cell of interest, up to 200ns:
- Divide the flux by the current flowing through resistor R_{out} at 200ns; the current is calculated from the voltage drop across the resistor divided by its resistance value (30.0Ω).

The self-inductance for each end cell of the prototype kicker magnet is approximately 139nH, and the self-inductance for the second and ninth cells is approximately 84nH. The average cell inductance for the eight central cells is approximately 76.5nH: the total self-inductance of the kicker magnet (L_t) is about 891nH.

The total propagation time, at the 1.6V (50%) level, for the 10 cells of the magnet is 26.2 ns whereas the propagation time through the 8 central cells is only 18 ns (see Fig. 1). The two end cells have increased self-inductance due to fringe fields at the ends of the magnet aperture, and this leads to a higher propagation delay in the end cells. The total capacitance to ground of the kicker magnet (C_t)

is given by:

$$C_t = \frac{\tau^2}{L_t} = \frac{(26.2ns)^2}{891nH} = 771pF \tag{10}$$

Hence, the characteristic impedance ($\sqrt{L_t/C_t}$) of the prototype kicker magnet is 34Ω. The discrepancy between the actual characteristic impedance and the 30Ω design value is mainly due to an error during the design procedure.

B. 1 MHz Excitation: Measurement Procedure

The field in the prototype kicker magnet was mapped while the magnet was driven with a 1MHz sine-wave. 50Ω stripline probes were used to measure the field in the aperture of the kicker magnet. The striplines were fabricated from 5 mm wide strips of circuit board clad with copper (0.06mm thick) on both sides. The dielectric material was 1.5 mm thick with a relative permittivity of 5. Three lengths of stripline were fabricated for the measurements; one version had a length of 30.5cm, equal to the length of the aperture of the 10 cell prototype magnet. The other two striplines had lengths equal to 9 cells and 8 cells of the prototype magnet. The one way propagation time in the 30.5cm stripline is approximately 2.3 ns.

The prototype magnet was terminated with a 30.0Ω resistor and excited with a 1 MHz signal. The 50Ω stripline was terminated at the remote end in a short circuit, and the other end was connected through a 50Ω coaxial cable to a matched termination in a Tektronix 11401 digital oscilloscope. The stripline was mounted into a milling machine x-y table drive which was set up to allow the aperture of the magnet to be mapped with good positional accuracy. The stripline was positioned in the magnet aperture in two different orientations: in one orientation the signal stripline of the probe was closer to the ground conductor of the kicker magnet and in the other orientation the signal stripline of the probe was closer to the high voltage conductor of the kicker magnet. Signals were measured with the magnet driven from one end, through a 30Ω source impedance, and terminated in 30Ω at the other end, and also with the order of magnet input and output reversed. The magnitudes of the four measured stripline signals were averaged (see section IV).

The steady-state input waveform to the magnet and the output signal from the stripline were measured and averaged in the digital oscilloscope for 512 scans to increase the signal to noise ratio.

C. 1 MHz Excitation: Absolute Measurements

Table 1 shows a comparison of the measured and calculated stripline signals. The two calculated stripline signals are for $Q = \infty$ and $Q = 5$ at a frequency of 1 MHz: an effective inductance of 76.5nH per cell is used. κ is proportional to the length of stripline probe of interest: for example for a stripline equal to a length of 10 cells $\kappa = 0.859$ ($= \frac{76.5nH \times 10 \text{ cells}}{891nH}$).

A Q of 5 reduces the magnetic component of stripline voltage by about 7% in comparison with a Q of ∞.

D. 1 MHz Excitation: Relative Measurements

TABLE 1
MEASURED AND CALCULATED STRIPLINE VOLTAGES FOR 9.26 V EXCITATION AT 1 MHz

Number of cells	Measured (mV)	κ	Calculated ($Q = \infty$) (mV)	Calculated ($Q = 5$) (mV)
10	13.4	0.859	14.4	13.9
9	12.4	0.773	13.0	12.5
8	11.6	0.687	11.5	11.2

PE2D [4] simulations of the prototype kicker magnet have been performed to predict the magnetic and electric field in the aperture of the magnet. Fig. 2 shows the predicted magnetic field along the center-line of the aperture, normalized to the magnetic field at the center of the aperture (8cm from the high voltage and ground conductor). Also plotted on Fig. 2 is the measured magnetic field along the center line of the aperture, normalized to the measured magnetic field at the center of the aperture. The error bars shown are ±0.5%: these error bars are derived by observing multiple samples of the field. A stripline equal to the length of the magnet was used to measure the magnetic field, so that fringe fields were not included: PE2D is a 2D code, and therefore the prediction does not include fringe fields either. The measured field has been averaged using the procedure described in subsection III.B. The normalized predicted and measured field are in agreement to within 1% (see Fig. 2).

IV. PSPICE CALCULATIONS

The circuit analysis software PSpice [6] has been utilized to simulate the kicker magnet and stripline probe. The equivalent circuit permits one to assess the effect of various phenomena, including resistive losses in the measurement circuit, and stray capacitance between the high voltage conductor and stripline probe.

The 10 cells of the prototype magnet are modelled individually. The stripline probe is modelled as 10, equal delay, sections. One section of the stripline probe model is inductively coupled to the corresponding cell of the magnet using a three winding transformer. The primary winding of the transformer model represents the inductance of a cell of the kicker magnet; the two secondary windings represent the inductance of the two striplines of the probe. A

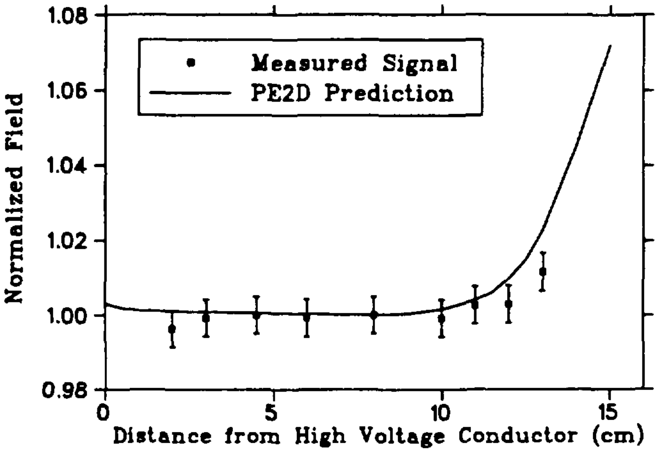

Fig. 2: Comparison of PE2D predictions and magnetic field measurements, both normalized to the field at the center of the aperture

coupling coefficient is specified from the primary to each of the two secondary windings of the transformer. Capacitance between the copper striplines, together with the self-inductance of the striplines, simulates the characteristic impedance and delay of the stripline probe. The simulations are carried out over a range of frequencies up to 10MHz. The kicker magnet is driven through, and terminated with, 30Ω resistors.

When the stripline probe is simulated as being terminated in a short-circuit at one end, and by the 50Ω input impedance of the oscilloscope at the other end, the following predictions are obtained:

1. At 1MHz a single way propagation delay of 2.3ns for the 30.5cm stripline probe reduced the predicted induced voltage by less than 0.02% in comparison to zero delay for the probe: the effect of the delay increases to almost 2% at 10MHz.
   For 'lossless' ($Q = \infty$) ferrite, at 1MHz ($\omega\tau = 0.165$), (2) and (9) give calculated voltage drops which are within 0.05% and 0.18%, respectively, of that obtained using PSpice. At a frequency of 4MHz ($\omega\tau = 0.658$), the corresponding errors are 0.7% and 2.5%. For ferrite with $Q = 5$ applying (9) at 1MHz gives a magnitude of voltage which is within 0.2% of that obtained using PSpice.

2. Skin-effect and proximity effect at 1MHz result in a calculated 0.1Ω of resistance in the 30.5cm long stripline probe. Assuming that there is also 0.5Ω of resistance associated with the coaxial cables connecting the stripline probe to the oscilloscope, the total effective parasitic resistance is 0.6Ω. This results in an error of approximately 1% in the predicted induced signal: this is consistent with (7). The error introduced by parasitic resistance cannot be removed by the signal averaging method described in subsection III.B. Hence it is desirable to minimize the total parasitic resistance associated with the stripline probe and connections to the oscilloscope. However, if the magnitude and distribution of parasitic resistance is known, its effect may be compensated for using (8).

3. If the kicker magnet is simulated as being driven from the end adjacent to the output end of the stripline probe, 5pF capacitance between the high voltage conductor and signal stripline of the probe results in an increase in the predicted signal below 6MHz ($\omega\tau \simeq 1$). When the kicker magnet is then driven from the opposite end, below 6MHz the 5pF capacitance results in a decrease in magnitude of the predicted signal. PSpice simulations show that for $\omega\tau \leq 1.0$, the average of these two signals removes the effect of capacitance between the high voltage conductor and stripline probe to within 0.05%. Hence for $\omega\tau \leq 1.0$ the PSpice results are in good agreement with (8).
   Repeating the above simulation but with the ground side of the stripline probe towards the high voltage conductor of the magnet: the average of the two signals, with the magnet driven from each end, removes the effect of capacitance between the high voltage conductor and stripline probe to within 0.3%.
   Hence it is unnecessary to carry out four sets of measurements: two sets of measurements are adequate.

When the stripline probe is simulated as being terminated at both ends with 50Ω, and stray capacitance between the high voltage conductor and probe exceeds 5pF, then the effect of the stray capacitance exceeds the effect of the magnetically induced voltage. Hence using the signal averaging technique described in subsection III.B results in a magnitude of signal which is still incorrect. This is in agreement with (7).

V. CONCLUSION

An equation has been derived (6), which considers the kicker magnet to be an ideal transmission line, which permits the absolute value of the measured field in a kicker magnet to be readily compared with the theoretical field, for small values of $\omega\tau$. The equation is then modified (7) to take into account the effect of parasitic capacitance between the high voltage conductor, and signal side of the stripline probe: parasitic resistance in the measurement loop is also considered. Equation (7) confirms the findings of measurements, which indicate that it is preferable to terminate the remote end of the stripline probe in a short-circuit. It is also shown that it is desirable to minimize parasitic resistance associated with the stripline probe and coaxial cables to the oscilloscope. Equation 9, which considers the kicker magnet as a lumped element, accounts for the effect of ferrite losses upon the signal measured with a stripline probe.

A comparison of PE2D predictions and magnetic field measurements, both normalized to the center of the aperture, show that the normalized predicted and measured fields are in good agreement.

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