national accelerator laboratory

TM-420
0413

KICKER MAGNET DESIGN

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Summary

The magnetostatic code LINDA has been used to calculate the electric field distribution of the TEM mode that would propagate in a ferrite kicker magnet if it were terminated in its characteristic impedance. The dual magnetic field is then determined on the median plane and across the surface bounded by the ferrite and the current conductor. This permits a calculation of the inductance per unit length and the field quality.

Evaluation of the pulse characteristics of a two magnet kicker supplied with shunt capacitors as in a pi-section filter is made using fast fourier techniques. As a result one finds that it is possible to design a 2-inch by 6-inch aperture kicker having a rise time of .33 μsec. with a field quality of 5 per cent over a 2-inch aperture.

Ferrite Kicker Magnet

Figure 1 presents the cross sectional details of an H-type magnet using a 1-inch thick ferrite yoke supplied with a pair of copper conductors as shown. A magnetic field was found for the

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dual problem in which the conductors were treated as infinite permeability iron, a line of symmetry being introduced to maintain the ferrite boundary in the gap as a line of constant magnetic flux. The magnetic field of this problem is identical with the electric field of the kicker problem when operating in the TEM mode. Thus, the effective gap of the magnetic field of the dual problem found by determining the ampere turns required to produce a central field of say, 1000 G. LINDA gave 4083.63 A for one half of the excitation. Thus the half gap W is given by

$$\frac{4\pi}{10} \cdot \frac{4083.63}{W \cdot 2.54} = 1000$$

or

$$W = 2.02 \text{ in} \tag{1}$$

or, the effective width of the magnetic field in the kicker problem is 2x2.02 = 4.04 inch.

The inductance per unit length of a uniform field in two dimensions is given by

$$L = 4\pi \frac{W}{G} \qquad \text{(emu)} \tag{2}$$

where G is the gap. In our case G=2.25 inch. Hence,

$$L = 4\pi \frac{4.04}{2.25} = 22.56 \text{ cm/cm} = .057 \text{ μHy/in} \tag{3}$$

All the parameters of the kicker magnet are summarized in Table 1. Figure 2 indicates the variation of the magnetic field in the median plane and across the ferrite surface.

Since the current density in the conductor is related to the surface magnetic field using

$$J = \frac{\omega\sigma}{Q} B_o e^{jQy}, \qquad \text{(emu)} \tag{5}$$

where σ is the conductivity of copper and

$$Q^2 = 4\pi\sigma\omega j \ , \qquad \text{(emu)} \tag{5}$$

one may determine a resistance associated with the power loss. Thus

$$R = 2\pi \sqrt{\rho f} \cdot \frac{\ell \int B_o^2 ds}{\left| \int B_o ds \right|^2} \ , \qquad \text{(emu)} \tag{6}$$

Where $\rho = 1/\sigma$, ℓ is the magnet length, and f is the frequency. The path length of integration is one half way around the inside of one conductor. By using the surface field variation shown in Figure 2 one finds that Eq. (6) gives the resistance shown in Figure 3.

Two Magnet Pi-Section Kicker

The circuit used for n-magnets in which the prototype section is pi-connected is shown in Figure 4. In filter theory notation[1]

$$Z_1 = R + j\omega L \qquad \left(R = \frac{R_o}{n},\ L = \frac{L_o}{n}\right) \tag{7}$$

$$Z_2 = \frac{1}{j\omega C} \qquad \left(C = \frac{C_o}{n}\right) \tag{8}$$

Then, the propagation constant Γ is

$$\cosh \Gamma = 1 + \frac{1}{2} \frac{Z_1}{Z_2} \tag{9}$$

and the characteristic impedance Z_o is

$$Z_o = \sqrt{\frac{Z_1 Z_2}{1+\frac{1}{4}\frac{Z_1}{Z_2}}}. \tag{10}$$

Figure 4 also indicates the current and voltage designations for cascaded filter sections. A transfer matrix connects the output pair (V_m, I_m) with the input pair (V_1, I_1). Thus

$$\begin{pmatrix} V_m \\ I_m \end{pmatrix} = \begin{pmatrix} \cosh\ (m-1)\Gamma & Z_o \sinh\ (m-1)\Gamma \\ \frac{1}{Z_o}\sinh\ (m-1)\Gamma & \cosh\ (m-1)\Gamma \end{pmatrix} \begin{pmatrix} V_1 \\ I_1 \end{pmatrix} \tag{11}$$

Note that m = n + 1 where n is the number of magnets.

In the source section one has

$$V_1 = \mathcal{E} - R_s I_1, \tag{12}$$

where $\mathcal{E}$ is the excitation voltage and R_s is the source resistance. The magnets are terminated in a resistor R_L. Thus

$$V_m = R_L I_m. \tag{13}$$

Combining Eqs. (11-13) one has

$$I_1 = \frac{Z_o \mathrm{ch}\ n\Gamma - R_L \mathrm{sh}\ n\Gamma}{R_L(Z_o \mathrm{ch}\ n\Gamma - R_s \mathrm{sh}\ n\Gamma) - Z_o(Z_o \mathrm{sh}\ n\Gamma - R_s \mathrm{ch}\ n\Gamma)}\mathcal{E} \tag{14}$$

and

$$I_m = \frac{Z_o}{R_L(Z_o \mathrm{ch}\ n\Gamma - R_s \mathrm{sh}\ n\Gamma) - Z_o(Z_o \mathrm{sh}\ n\Gamma - R_s \mathrm{ch}\ n\Gamma)}\mathcal{E} \tag{15}$$

If, in Eq. (11) one replaces m by k one finds in particular

$$V_k = (\mathcal{E}-R_a I_1)\ \mathrm{ch}\ (k-1)\Gamma + Z_o I_1\ \mathrm{sh}\ (k-1)\Gamma. \tag{16}$$

The current through the k^{th} magnet is

$$A_k = \frac{V_k - V_{k+1}}{R+j\omega L} \tag{17}$$

or

$$A_k = \frac{1}{R+j\omega L}\left\{(\mathcal{E}-R_s I_1)\left[\mathrm{ch}(k-1)\Gamma - \mathrm{ch}\ k\Gamma\right] + Z_o I_1\left[\mathrm{sh}(k-1)\Gamma - \mathrm{sh}\ k\Gamma\right]\right\} \tag{18}$$

In kicking the beam the sum current is of interest. Thus*

$$A_1 + A_2 + \cdots A_n = \frac{1}{R+j\omega L}\left[(\mathcal{E}-R_s I_1)(1-\mathrm{ch}\ n\Gamma) - Z_o I_1 \mathrm{sh}\ n\Gamma\right]. \tag{19}$$

Finally the power absorbed by the magnets is

$$P(\omega) = \mathrm{Real}\ (\mathcal{E} I_1^* - V_1 I_1^* - V_m I_m^*). \tag{20}$$

From Eqs. (14-15) one may find the admittances

$$I_1 \equiv Y_1 \mathcal{E} \qquad I_m \equiv Y_m \mathcal{E} \tag{22}$$

Then, the internal power spectrum becomes

$$P(\omega) = \mathcal{E}\ \mathcal{E}^*\ \mathrm{Real}\ (Y_1^* - R_s Y_1 Y_1^* - R_\ell Y_m Y_m^*). \tag{23}$$

Fast Fourier Transforms

The response of a two magnet kicker to a square wave voltage excitation has been analyzed using a fast fourier transform technique[(2)]. Fourier analysis of a 20 μsec. rectangular voltage

*Strictly speaking local time should be used in adding the currents. However, since the traversal time is less than 6.8 nsec this correction is negligible.

pulse repeated every 40 μsec. yields coefficients which are then modified by the admittance function determined from Eq. (19). Subsequent fourier synthesis gives the time variation of the mean magnet current. By folding Eq. (23) into this process one may simultaneously obtain the power dissipated in the magnets.

Figure 3 shows the variation of the propagation constant with frequency. Figure 5 shows the time response of the mean magnet current for three distinct shunt capacitances. Clearly the total capacitance, C_o = ,005 μF gives the best response. In this case the rise time at 99.8 per cent of final current is .33 μsec.. Figure 6 shows the internal power spectrum. From this one finds that the total energy absorbed by the resistive conductors is .097 Joule per pulse. Table 2 summarizes the two magnet kicker circuit parameters.

Acknowledgement

Desirable kicker magnet specifications were supplied by H. T. Edwards. Equivalent pulse forming network parameters and trial capacitance suggestions were supplied by J. D. McCarthy.

1. W. R. Smythe, Static and Dynamic Electricity, McGraw-Hill Book Co., Inc., 1939, page 366.

2. J. P. Boris, Plasma Physics Laboratory, Princeton University.

Table 1. Kicker Magnet Parameters

Gap (Ferrite to Ferrite)	2.25	in
Physical Aperture	5.75	in
Conductor Gap	2.00	in
Conductor Aperture	3.25	in
Conductor Thickness	.125	in
Conductor Corner Radius	.125	in
Effective Width of Magnetic Field	4.04	in
Inductance per Unit Length	.0566	μHy/in
Transfer constant	.220	G/A
Field Quality ($\Delta B/B$ at 1 inch)	5	percent

Table 2. Two Magnet Kicker Circuit Parameters

Peak Voltage pf Pulse Forming Network (PFN)	60kV
Characteristic Impedence of PFN	25Ω
Total Inductance of Kicker Magnets	5.0μHy
Total Capacitance of Kicker	.005μF
Total Length of Kicker Magnets	80 in
Capacitor Connection	Pi-Section
Number of Magnet Sections	2
Resistivity of Conductor	.772μΩ-in
Terminating Resistance	25Ω
Internal Energy Dissipation per Pulse	.097J
Peak Excitation Current	1200A
Median Plane Peak Magnetic Field	264G
Peak Magnetic Field in Ferrite	866G
Rise Time (99.8 per cent of final value)	.33μsec.

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KICKER MAGNET

$L_0 = .0566\ \mu Hy/in$

$Z_0 = 669\ \Omega$

$T_0 = .220\ G/A$

$\frac{\Delta B}{B} = 5$ percent at 1 inch

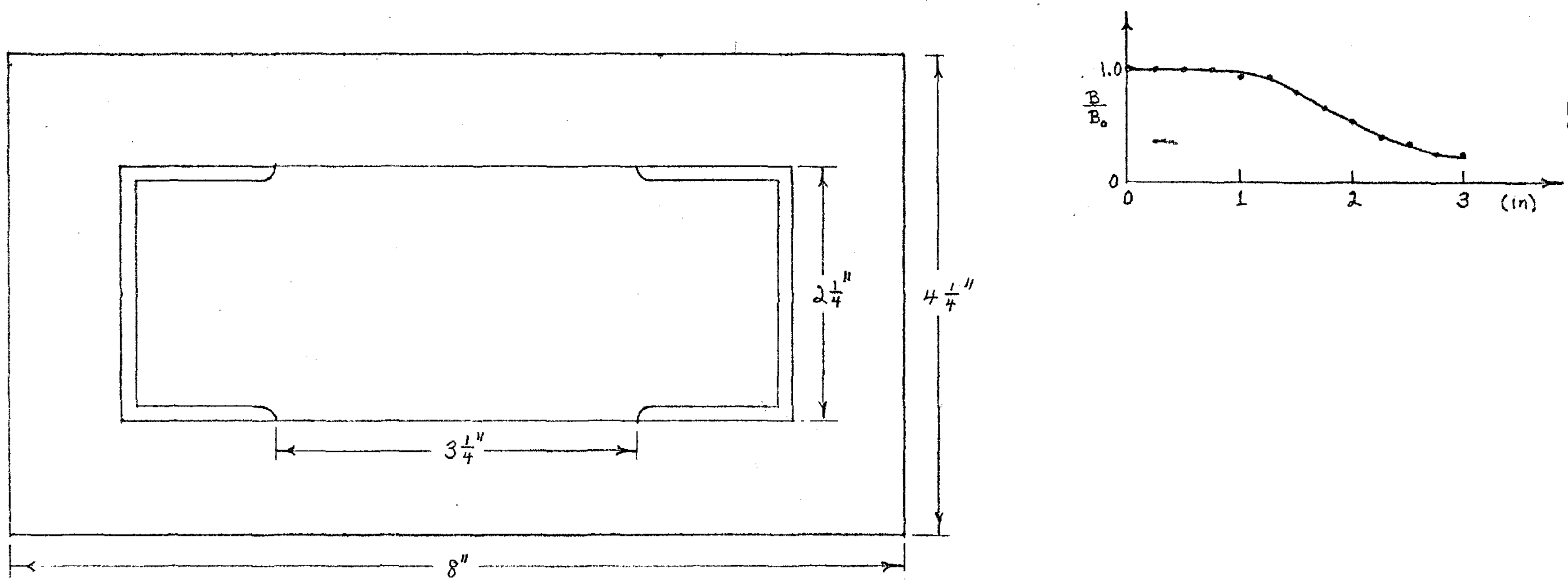


Figure 1

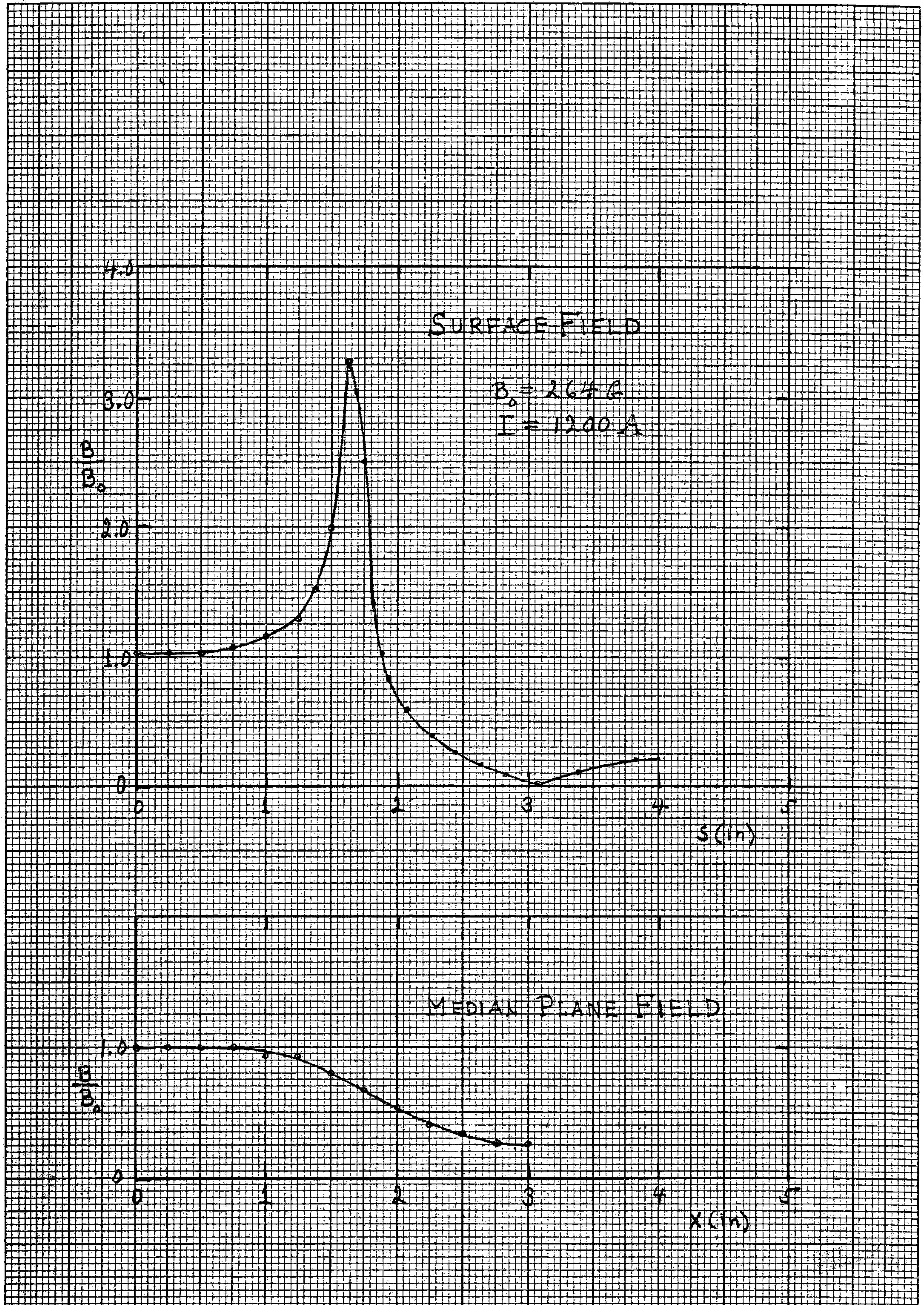

SURFACE FIELD
B_o = 264 G
I = 1200 A
B/B₀
4.0
3.0
2.0
1.0
0
0
1
2
3
4
5
S (in)
MEDIAN PLANE FIELD
B/B₀
1.0
0
0
1
2
3
4
5
X (in)

Figure 2

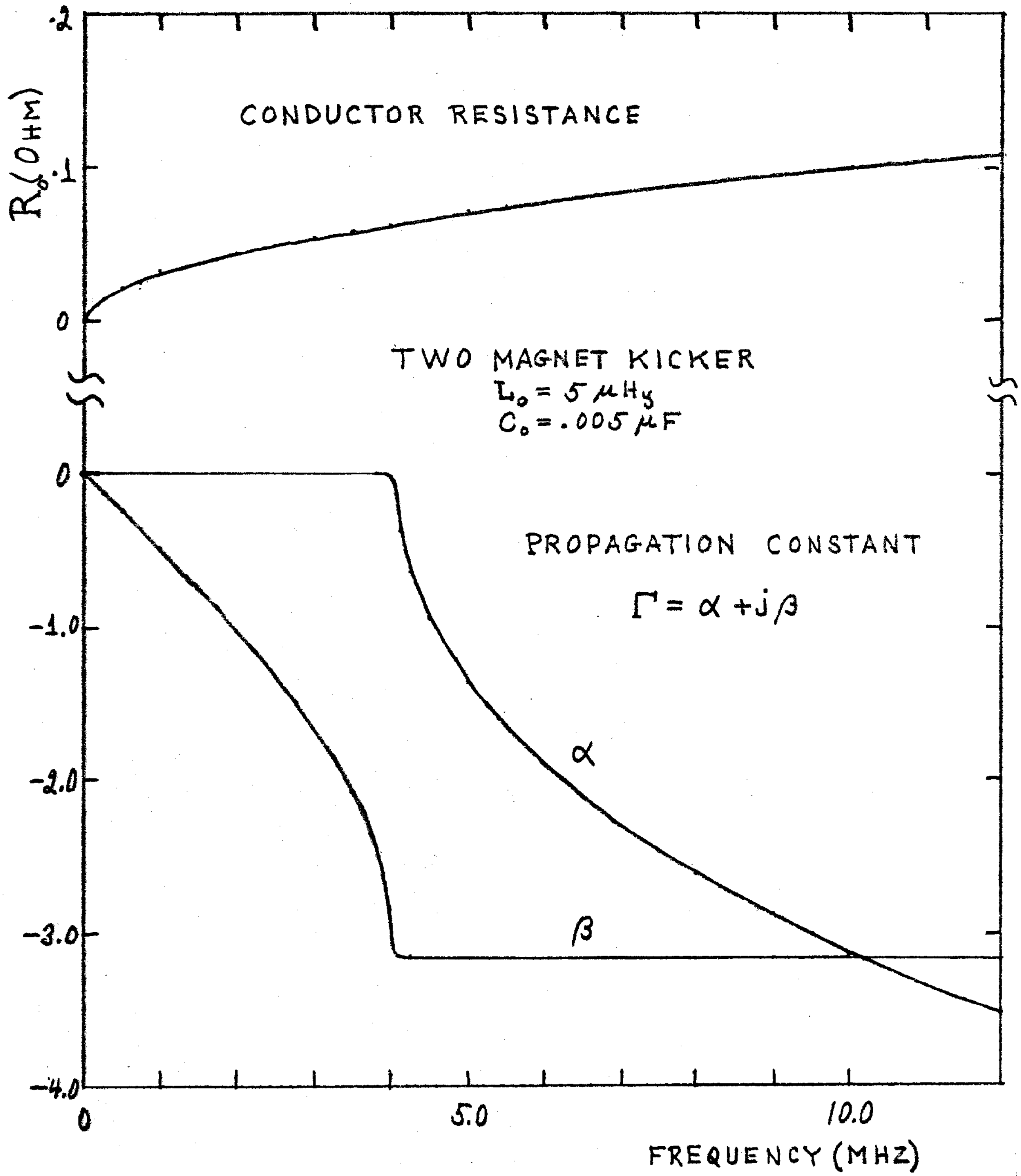
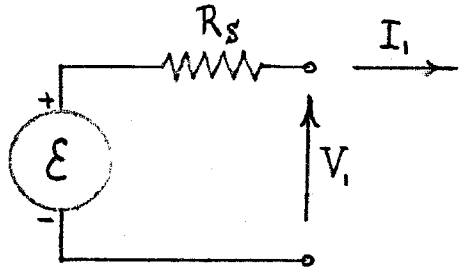
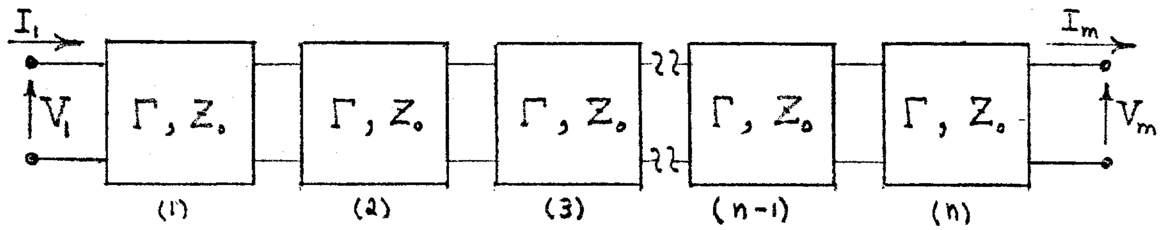

CONDUCTOR RESISTANCE
R_o (OHM)
.2
.1
0
TWO MAGNET KICKER
$L_o = 5\ \mu Hy$
$C_o = .005\ \mu F$
0
-1.0
-2.0
-3.0
-4.0
PROPAGATION CONSTANT
$\Gamma = \alpha + j\beta$
α
β
0
5.0
10.0
FREQUENCY (MHZ)

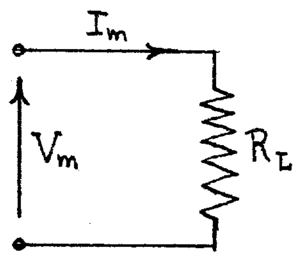
Figure 3



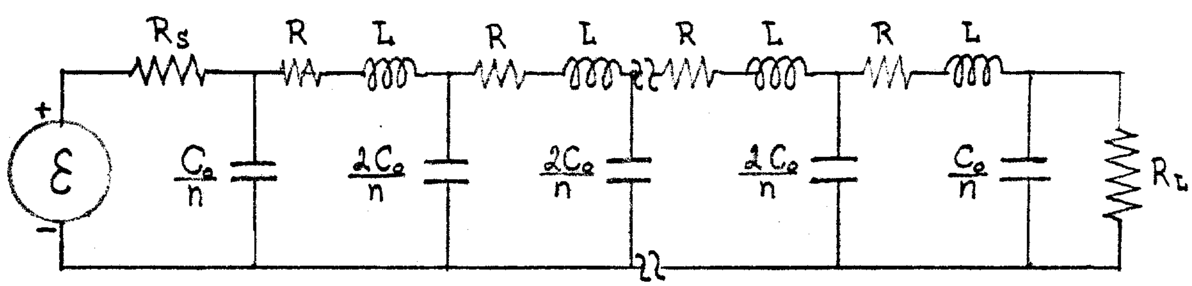
SOURCE SECTION



CASCADED FILTER



LOAD SECTION



SIMULATED KICKER MAGNET CIRCUIT

Figure 4

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Subject

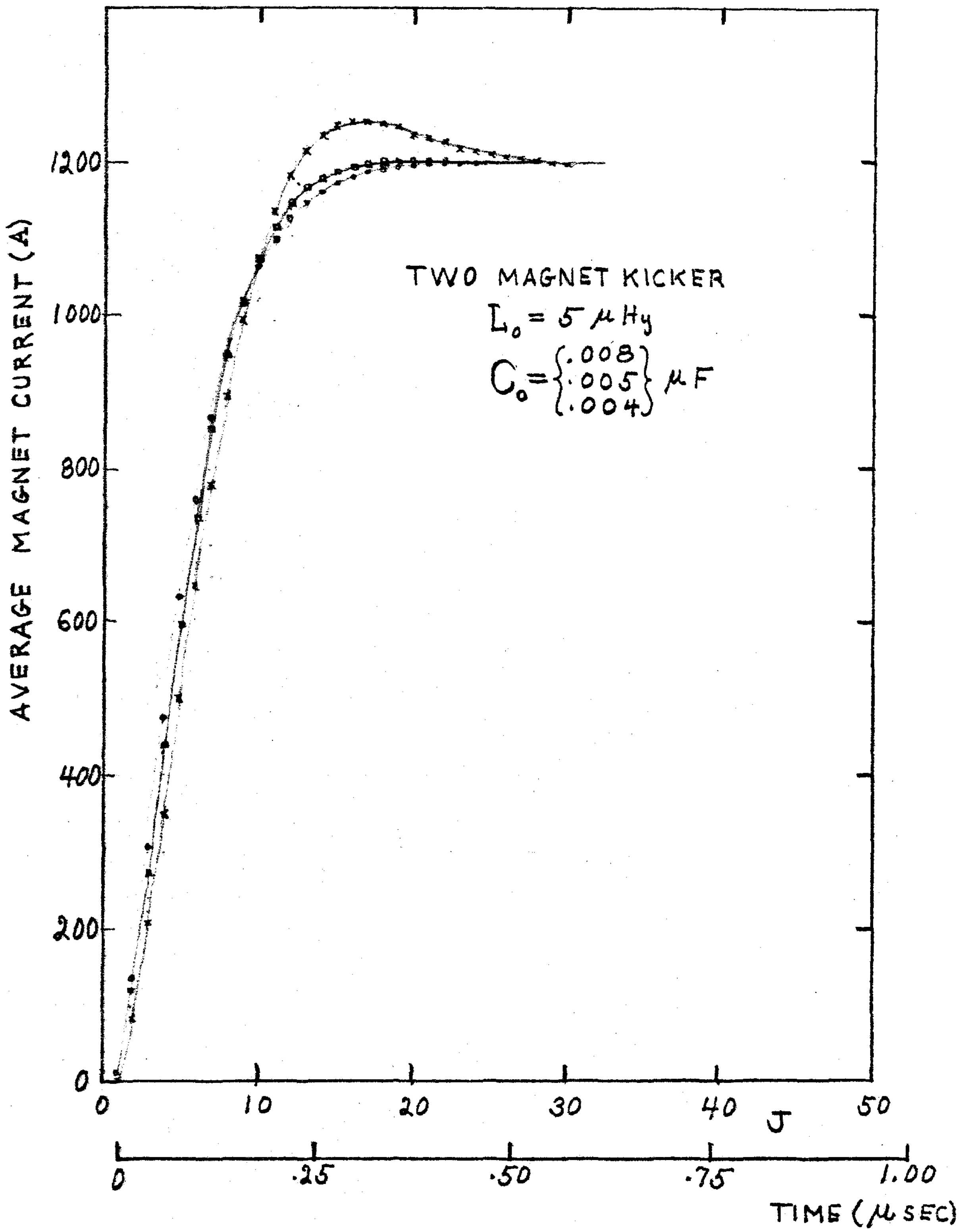

Figure 5

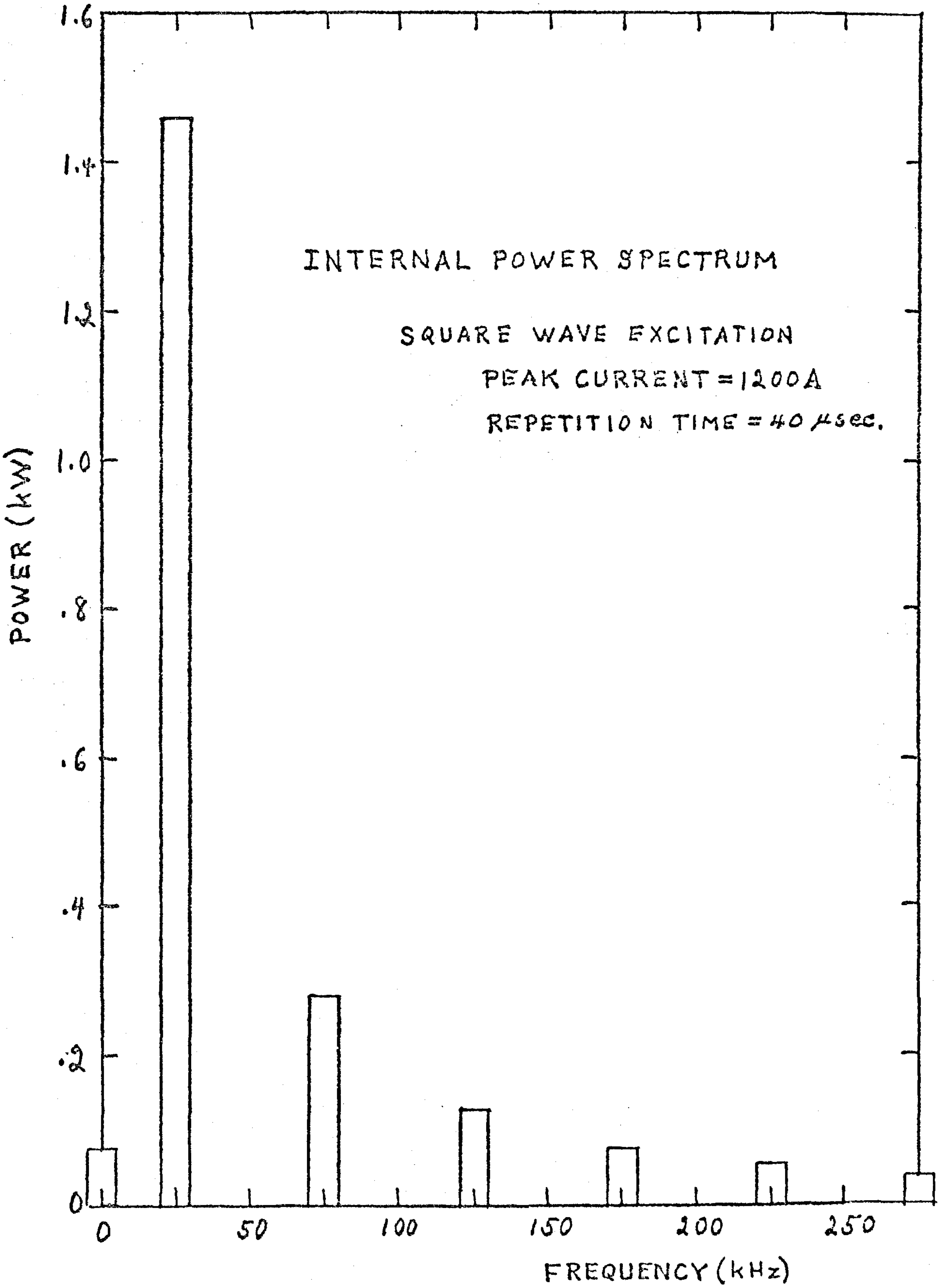
INTERNAL POWER SPECTRUM
SQUARE WAVE EXCITATION
PEAK CURRENT = 1200A
REPETITION TIME = 40 μsec.
POWER (kW)
1.6
1.4
1.2
1.0
.8
.6
.4
.2
0
0
50
100
150
200
250
FREQUENCY (kHz)

Figure 6