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BASIC PRINCIPLES GOVERNING THE DESIGN
OF MAGNETIC SWITCHES

D. L. Birx
E. J. Lauer
L. L. Reginato
J. Schmidt
M. Smith

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Lawrence
Livermore
Laboratory

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BASIC PRINCIPLES GOVERNING THE DESIGN OF MAGNETIC SWITCHES

ABSTRACT

The idea of using saturable reactors as the basis of high power pulse generators is not a new concept, but there have been few recent applications of this technology. Here the principle of magnetic pulse generation is briefly described and some of the basic guidelines used to design these circuits are discussed. A demonstration of the principles by a small scale pulse amplifier is presented, and finally there is an extrapolation to a large scale system.

INTRODUCTION

The use of saturable reactors for high power pulse generation was first described by Melville¹ in 1951, but with the advent of solid state technology and improvements in thyratrons there has been little recent application of this technology. Current interest in very high power levels ($\geq 10^{10}$ W) at high repetition rates has forced us back into the archives to re-examine the properties of saturable reactors as switches. The only switches presently available in this power range are high-pressure gas and liquid-discharge switches. Of these two choices only the high-pressure-gas switches are usable at high repetition rates, but even they are limited to of order 1 kHz. While a magnetic switch has never been constructed to operate at this power level, the only obvious limitation on repetition rate is the time required to charge the first stage. This paper outlines some of the inherent problems associated with the design of very high-power magnetic switches and attempts to show that, while it is difficult to build such a switch, it does indeed appear feasible.

The basic principle behind magnetic switching is to use the large changes in permeabilities exhibited by saturating ferri- (ferro-) magnetic material to produce large changes in impedance. The standard technique for capitalizing on this behavior is illustrated in Fig. 1. By using multiple stages as shown it is possible to achieve an effective change in impedance much larger than can be obtained from a single stage. The operation of this circuit can be described as follows.

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Capacitor c_1 is charged through L_0 until L_1 saturates; L_1 is chosen to have a saturated inductance much less than L_0 . Once L_1 saturates, c_2 will begin to charge from c_1 through L_1 , but because $L_1 \ll L_0$, c_2 charges much more rapidly than c_1 did. The process continues^{sat} through the successive stages until c_n discharges into the load.

The operation of a single stage is depicted in Fig. 1b. Immediately after saturation of inductor L_{n-1} , capacitor c_{n-1} begins to discharge through L_{n-1} into capacitor c_n . The values of the capacitors are chosen to be approximately equal in order that capacitor c_{n-1} be fully discharged when c_n is fully charged. Saturable inductor L_n is designed so that it is approaching a saturated state when c_n is fully charged. When L_n saturates capacitor c_n will start to discharge through L_n into c_{n+1} .

OPERATION

In this section a more quantitative description of the circuit operation is presented. The analysis is based on saturable inductors with toroidal geometries, and for the sake of clarity several simplifying approximations have been introduced. All circuit components will be assumed lossless and all extraneous inductances ignored. Also, the expressions for saturated inductance will assume that the area enclosed by the turns is simply the core cross sectional area, while in practice insulation between turns will result in a larger saturated inductance.

Saturation of an inductor occurs when the magnetic field in the inductor core reaches the saturation magnetization. This assumes of course that the core material is ferri- or ferromagnetic material. Saturation is measurable as a large incremental change in the material permeability. A typical curve of B versus H for ferri- (ferro-) magnetic materials is shown in Fig. 2. Here saturation appears as a segment in the curve where $\left| d^2B/dH^2 \right|$ is large.

According to Maxwell,

$$\int \mathbf{E} \cdot d\mathbf{l} = \mathbf{V}_L = N \frac{\partial \Phi}{\partial t} = NA \frac{\partial B}{\partial t} \quad , \quad (1)$$

$$\int \mathbf{V}_L dt = NA \Delta B \quad , \quad (2)$$

and if the core has been reset,

$$\int_0^{\tau_{sat}} V_L dt = NA(-B_r + B_s) = NA \Delta B_s, \quad (3)$$

where N is the number of turns around the core, A the area of the core, and $B_r(B_s)$ the remanent (saturating) magnetic field.

Returning now to Fig. 1a, it can be shown that the time required to charge capacitor c_n after L_{n-1} saturates is given by

$$\tau_{charge}^{c_n} = \tau_{discharge}^{c_{n-1}} = \pi \left(L_{n-1}^{sat} \cdot \frac{c_{n-1} c_n}{c_{n-1} + c_n} \right)^{1/2} \quad (4)$$

but if $c_n = c_0$ all n , then

$$\tau_{charge}^{c_n} = \pi \left(\frac{L_{n-1}^{sat} \cdot c_0}{2} \right)^{1/2} \quad (5)$$

The time required to charge capacitor c_n should be approximately equal to the time to reach B_{sat} in inductor L_n . Therefore

$$\tau_{sat}^{L_n} \approx \tau_{charge}^{c_n} = \frac{\Delta B_s N_n A_n}{\langle V_c \rangle} \quad (6)$$

Ideally

$$\langle V_c \rangle = V_{c_0} \int_0^{\pi/\omega} \frac{(1 - \cos \omega \tau)}{2} dt = \frac{V_{c_0}}{2}; \quad (7)$$

therefore

$$\tau_{charge}^{c_n} = \frac{2 \Delta B_s}{V_{c_0}} N_n A_n, \quad (8)$$

where V_{c_0} is the peak charge voltage of capacitor c_n . After inductor L_n saturates we find:

$$\mu_n = \frac{\mu_n^{\text{sat}}}{2} W_n N_n \ln \left(\frac{R_{\text{on}}}{R_{\text{in}}} \right) \approx \frac{\mu_n^{\text{sat}}}{2\pi} \frac{N_n^2 A_n}{\langle R \rangle} \quad (9)$$

$$\approx \frac{\mu_n^{\text{sat}}}{\text{volume}} \frac{N_n A_n}{2}, \quad (10)$$

where W_n is the axial width of the toroid and $R_{\text{on}}(R_{\text{in}})$ the core outer (inner) radius. Combining Eqs. (5) and (8) we see that

$$L_{n-1}^{\text{sat}} = \frac{2}{C_0} \left(\frac{2}{\pi^2} \frac{\Delta B_s}{V_c} N_n A_n \right)^2. \quad (11)$$

Introducing Eq. (10) gives:

$$\frac{L_n^{\text{sat}}}{L_{n-1}^{\text{sat}}} \approx \frac{\mu_n^{\text{sat}}}{\text{volume}_n} \cdot \pi^2 \frac{\left(\frac{C_0}{2} V_c \right)^2}{4 \cdot \Delta B_s^2} \approx \frac{\text{energy}}{\text{volume}_n} \left(\frac{\mu_n^{\text{sat}} \cdot \pi^2}{4 \cdot \Delta B_s^2} \right); \quad (12)$$

therefore

$$\text{volume}_n = \left(\frac{\tau_{\text{charge}}^{\frac{c_n}{c_{n+1}}}}{\tau_{\text{charge}}} \right)^2 \cdot \text{energy} \cdot \left(\frac{\mu_n^{\text{sat}} \cdot \pi^2}{4 \cdot (\Delta B_s)^2} \right), \quad (13)$$

where

$$\frac{\tau_{\text{charge}}^{\frac{c_n}{c_{n+1}}}}{\tau_{\text{charge}}} = \left(\frac{L_n^{\text{sat}}}{L_{n+1}^{\text{sat}}} \right)^{1/2} = \text{gain}. \quad (14)$$

It can also be shown that if the core materials are identical, optimal efficiency is achieved when all core volumes are equal.² It becomes apparent from the above analyses that for satisfactory operation of a multistage circuit the following conditions must be met:

- (a). $L_{n-1} \gg L_n^{\text{unsaturated}};$
- (b). $L_{n+1}^{\text{unsaturated}} \gg L_n^{\text{unsaturated}};$

- (c). Saturation of inductor L must occur at π/ω on the charging voltage for c_n ;
- (d). $c_n \approx c_0$ for all N; and
- (e). The saturated impedance of L_n , the final inductor, must be less than the load impedance.

A criteria of 20 for $\gg$ has been recommended,¹ and experimental work here supports that opinion.

Combining conditions (a) and (b) yields

$$(c). \frac{L_n^{\text{unsaturated}}}{L_n^{\text{sat}}} = \frac{\mu^{\text{unsat}}}{\mu^{\text{sat}}} \geq 400 .$$

This condition allows us to generate an approximate expression for the maximum practical compression factor per stage:

$$\frac{\tau_{n-1}}{\tau_n} = \left(\frac{L_{n-1}^{\text{unsat}}}{L_n^{\text{sat}}} \right)^{1/2} \leq \left(\frac{\mu^{\text{unsat}}}{\mu^{\text{sat}} \cdot 20} \right)^{1/2} \quad (15)$$

Hence, given the desired overall compression factor, the minimum number of stages can be determined from the material properties.

It should also be noted here that in general the effective unsaturated permeability is a function of the saturation time unless eddy current and spin relaxation losses can be neglected. In addition, the saturated permeability can be a strong function of the applied H field up to sever 1 thousand A-T/m and in actuality is never identically equal to μ_0 . These topics are addressed in more detail in Appendix A.

THE OUTPUT STAGE

In many of the applications for magnetic pulse generators a rectangular output pulse is desired. In the above analyses the output from the successive stages were of the form $V_0(1 - \cos \omega t)$ into a capacitive load. Producing a

rectangular pulse into a resistive load generates very stringent requirements on the output stage.

In order to produce a rectangular pulse, the final stage capacitor must in reality be a pulse forming line (PFL) or pulse forming network (PFN). Providing a uniform voltage distribution along a PFL requires that

$$\tau_{\text{charge}} \gg \tau_{\text{output pulse}} \quad (16)$$

It is also a desirable condition that the output pulse risetime be much less than the pulse period:

$$\frac{L_{\text{final}}}{R_{\text{out}}} \ll \tau_{\text{output pulse}} \quad (17)$$

Rewriting Eqs. (16) and (17) in a more quantitative form gives

$$\tau_{\text{charge}} \geq G_1 \cdot \tau_{\text{output pulse}} \quad (18)$$

$$\frac{L_{\text{final}}}{R_{\text{out}}} \leq \frac{\tau_{\text{output pulse}}}{G_2} \quad (19)$$

where G_1 and G_2 are chosen from the requirements on the output pulse dictated by the load.

Combining Eqs. (18) and (19) we obtain

$$\frac{L_{\text{final}}}{R_{\text{out}}} \leq (G_1 G_2)^{-1} \tau_{\text{charge}} \quad (20)$$

$$L_{\text{final}} \leq \frac{(G_1^2 G_2)^{-1} \tau_{\text{charge}}^2 R_{\text{out}}}{\tau_{\text{output pulse}}} \quad (21)$$

Now applying Eq. (5) gives

$$\frac{L_{\text{final}}^{\text{sat}}}{L_{\text{final}-1}^{\text{sat}}} \leq \frac{\pi^2 \frac{c_0}{2} R_{\text{out}} \cdot (G_1^2 \cdot G_2)^{-1}}{\tau_{\text{output pulse}}} \quad (22)$$

In the case that the output PFL is a coaxial transmission line,

$$\frac{1}{2} C_0 V_c^2 = \frac{r_{\text{output}}}{R_{\text{out}}} \left(\frac{V_c}{2} \right)^2, \quad (23)$$

and Eq. (22) can be rewritten as

$$(Gain)^2 = \frac{L_{\text{final}}^{\text{sat}}}{L_{\text{final-1}}^{\text{sat}}} \leq \frac{\pi^2}{4} \left(G_1^2 + G_2 \right)^{-1}. \quad (24)$$

Combining Eq. (24) with Eq. (15) yields

$$\frac{80 G_1^2 G_2}{2} \leq \frac{V_{\text{unsat}}}{V_{\text{sat}}}. \quad (25)$$

Although this relation was derived for a coaxial PFL, it applies to all PFL's.

A SMALL-SCALE, EXPERIMENTAL MAGNETIC-PULSE GENERATOR

As a demonstration of the principles outlined above, a three-stage magnetic-pulse generator was designed and constructed. The goal was to compress the energy from a 15 μ s charging pulse to a rectangular output pulse of 60 ns. In practice it was more convenient to charge the first stage capacitor to full voltage beforehand and then switch it into the circuit. Under these conditions the time required to saturate the first stage inductor was only 7.5 μ s.

The pulse amplifier is schematically illustrated in Fig. 3. The output stage consisted of a water-filled transmission line three feet in length. The characteristic impedance of this coaxial PFL was 1.6 Ω . The 20-nf capacitors of the first two stages were chosen to match the capacitance of the PFL.

A summary of the design data and a comparison with actual performance is tabulated in Table 1. The experimental results are presented pictorially in Fig. 4.

This system was constructed from available materials and therefore not fully optimized. Even under these conditions the efficiency was approximately 70%. It is interesting to note the effect on efficiency of deviating from calculated optimum design parameters. In the first stage, by using a core a factor of 2 too large, we doubled our losses in that stage. This agrees with the theory that quick and dirty is usually dirtier than quick.

TABLE I. Design data for the three-stage magnetic-pulse compressor.

Design parameter	1st stage	2nd stage	3rd stage
Pulse energy	2.25 J	2.25 J	2.25 J
Charge Voltage	15 kV	15 kV	15 kV
Capacitance	20 nF	20 nF	20 nF (PFL)
$\tau_{\text{charge}} = \frac{2 \cdot \Delta B_s}{V} \text{ N A}$	15 μs (effective)	1 μs	0.18 μs
$\tau_{\text{discharge}}$	1 μs	0.18 μs	60 ns with 9 ns-L/R
Gain	15 (effective)	5.5	5 (effective)
Material	Ni ₅₀ Fe ₅₀	TDK P ferrite	TDK P ferrite
ΔB_s	2.2 T	0.45 T	0.45 T
Volume = $\frac{\text{Energy} \cdot \left(\frac{\mu \cdot \pi^2}{4 \Delta B_s^2} \right)^2}{(\text{gain})^2}$	$7.5 \cdot 10^{-4} \text{ m}^3$	$1.16 \cdot 10^{-3} \text{ m}^3$	$1.16 \cdot 10^{-3} \text{ m}^3$
Core volume (closest available)	$1.65 \cdot 10^{-3} \text{ m}^3$	$1.35 \cdot 10^{-3} \text{ m}^3$	$1.35 \cdot 10^{-3} \text{ m}^3$
Core dimensions (in.) $R_o \times R_i \times w$	$9.25 \times 4.625 \times .5$	$6.125 \times 3.375 \times 1.0$	$6.125 \times 3.375 \times 1.0$
Core loss (based on actual volume)	0.26 J	0.14 J	0.14 J
No. turns required	32	10	2
Measured parameters			
Pulse energy	1.95 J	1.8 J	1.6 J
Energy lost per stage (including incomplete discharge of capacitors)	0.3 J	0.15 J	0.2 J
τ_{charge}	15 μs (effective)	0.8 μs	0.25 μs
$\tau_{\text{discharge}}$	1.0 μs	0.25 μs	15 ns - $L_f/1.67$
Compression factor	15 (effective)	4	5.7 (effective)

The largest deviation of the measured performance from the calculated performance appeared in the final stage. The predicted risetime of the output pulse was 9 ns while the measured value was 15 ns. Two factors which contributed to this error were the added inductances associated with connecting leads and insulation between turns, and the final saturated permeability of the ferrite core that was assumed to be equal to μ_0 in the calculations. It has been shown that ferrite switches can be used to produce risetimes shorter than a few ns. An example of this is presented in Appendix C.

In general the authors feel that the agreement between theory and experiment was quite good.

EXTRAPOLATION TO A LARGE SCALE MAGNETIC SWITCH

With the confidence gained from the performance of our small scale magnetic switch, we believe the obvious next step is to design a bigger and better version, but first it is important to take a look at how things change as the pulse energy increases.

Referring to the previous analyses we can quickly derive the following simple scaling laws:

- maximum gain is independent of pulse energy;
- number of stages is independent of pulse energy;
- efficiency is independent of pulse energy; and
- core volume varies linearly with pulse energy.

These relationships provide an indication of the major problem involved in going to larger and larger systems. Magnetic switches for large pulse energies will be bulky and heavy. It is also worth noting that multistage switches require multiple capacitive storage units each capable of storing the full pulse energy, and the capacitor volume will also vary linearly with pulse energy.

It is an interesting exercise to simply extrapolate our previous design to a multistage magnetic switch capable of supplying a 250-kV pulse of 50-ns duration into a 10-ohm load. We will design for a charging time of 10 μ s and an output 10% to 90% risetime of 10 ns. The information from which we will begin to design is presented in Table II.

TABLE II. Design data for large-scale magnetic pulse generation.

Property	First stage	Second stage	Third stage
Energy ^a	300 J	300 J	300 J
charge	10 μ s	1.2 μ s	0.15 μ s
discharge	1.2 μ s	0.15 μ s	50 ns with 5 ns = L/R
Gain	8	8	6
Capacitance	10 nF	10 nF	10 nF-Blumlein
Voltage	250 kV	250 kV	250 kV

^aFor simplicity we have neglected losses. In practice one would probably have to start with approximately 400 J for 300 J out.

There exist various choices for the core materials used in the different stages. The predicted performance and volume requirements of those which are believed to perform best are given in Table III.

Although the core volumes required are not totally prohibitive, their sizes and weights are not negligible, (the densities of the various materials vary between 5 and 7 g/cm³). In particular, when the additional capacitor requirements are considered, discharge switches look very attractive. It is only for applications requiring high repetition rates or high reliability that magnetic switches begin to look interesting again.

This study was initiated by a question which we are now in a position to answer. The answer to the question of "whatever happened to magnetic switches" is "someone invented the triggered spark gap."

TABLE III. Projected core requirements for the large-scale magnetic switch (packing factors are not considered).

	Core material	Core volume required	Predicted core loss
First stage ($\tau_{\text{charge}} = 10 \mu\text{s}$, $\tau_{\text{discharge}} = 1.2 \mu\text{s}$, energy = 300 J)	Metglass ^a 2605 2 mil tape	$6.6 \cdot 10^{-3} \text{ m}^3$	0.75 J
	Ni ₅₀ Fe ₅₀ 1 mil tape	$1.0 \cdot 10^{-2} \text{ m}^3$	1.2 J
Second stage ($\tau_{\text{charge}} = 1.2 \mu\text{s}$, $\tau_{\text{discharge}} = 0.15 \mu\text{s}$, energy = 300 J)	Metglass 2605 0.8 mil tape	$6.6 \cdot 10^{-3} \text{ m}^3$	1 J
	Ni ₅₀ Fe ₅₀ 1/2 mil tape	$1.0 \cdot 10^{-2} \text{ m}^3$	2 J
	Ni ₅₀ Fe ₅₀ 1 mil tape	$1.0 \cdot 10^{-2} \text{ m}^3$	4 J
Third and output stage ($\tau_{\text{charge}} = 0.15 \mu\text{s}$, $\tau_{\text{discharge}} = 50 \text{ ns}$, $L_f/R = 4 \text{ ns}$, energy = 300 J)	TDK P11 Bs = 0.45 T	$1.65 \cdot 10^{-1} \text{ m}^3$	16.5 J
	TDK H7C1 ΔBs = 0.63 T	$8.44 \cdot 10^{-2} \text{ m}^3$	8 J
	Metglass 2605 0.8 mil tape ΔBs = 3 T	$3.72 \cdot 10^{-3} \text{ m}^3$	2 J

^aReference to a company or product name does not imply approval or recommendation of the product by the University of California or the U.S. Department of Energy to the exclusion of others that may be suitable.

SUMMARY

There are many details and additional problems we have not addressed here, but we have tried to discuss the major difficulties and to develop an approximate model for magnetic switch performance.

In conclusion it indeed appears possible to construct magnetic switches, but at considerable increases in the cost, size, and weight of systems using discharge switches. The primary advantages lie in their inherent reliability and high-repetition-rate capability.

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APPENDIX A: DETERMINATION OF μ_{SAT} AND μ_{UNSAT}

A. Determination of μ_{sat}

Low field measurements of many magnetic materials give the appearance of saturation at fields slightly above H_c . In fact μ_{sat} is never equal to μ_0 , but will begin to approach μ_0 at the anisotropy field H_k . Some measurements on Metglass 2826 conducted at Allied Chemical^{3,4} (see Fig. A-1) illustrate this affect. Measurements on various other materials are depicted graphically in Fig. A-2.

When designing a magnetic amplifier, one must take this behavior into account in order to achieve satisfactory operation.

B. Determination of μ_{unsat}

Because of frequency-dependent losses, the saturation field H_{sat} is larger at high frequencies than is the dc value. Therefore, the high-frequency effective μ_{unsat} will be less than that indicated by low frequency measurements. The saturation magnetization B_s is relatively independent of frequency.

In the brief analysis which follows below we will try to generate an approximate relationship between μ_{unsat} and the energy loss in the core:

$$\frac{\text{Energy loss}}{\text{Volume}} = \int_{B_r}^{B_s} H \cdot dB = \langle H \rangle \cdot \Delta B_s ,$$

but $\Delta B_s \approx \bar{\mu}_{unsat} \cdot H_{sat}$; and if $\langle H \rangle \sim H_{sat}/2$ then

$$\frac{\text{Energy loss}}{\text{Volume}} \approx \frac{(\Delta B_s)^2}{2 \cdot \bar{\mu}_{unsat}} ,$$

and

$$\bar{\mu}_{unsat} = \frac{(\Delta B_s)^2}{2 \cdot \left(\frac{\text{Energy lost}}{\text{Volume}} \right)} .$$

APPENDIX B: CALCULATION OF CORE LOSSES

There are three primary contributions to the core loss, the dc anisotropy energy, eddy current losses, and spin relaxation viscous damping. The dc anisotropy energy can be determined by measuring

$$\int_{B_r}^{B_s} B \cdot dH$$

at low frequencies, but the eddy current and spin relaxation losses vary with frequency.

The losses in the metallic-tape-wound cores is strongly influenced by the above frequency dependent effects. Examination of these cores indicates that a saturation wave begins at the surface of the tapes and propagates toward the center. The propagation velocity is simply the domain wall velocity³ and is given by

$$v = \left(\frac{2 B_s}{\beta} \right) (H - H_0) \quad [\text{CGS}] ,$$

where H_0 is the dc saturation field and is given by

$$\beta = \beta_e + \beta_r ,$$

with β_e (β_r) being the eddy current (spin relaxation) viscous damping parameter. The saturation field of a tape of thickness d is approximately

$$H \approx H_0 \text{ dc} + \frac{d \cdot \beta}{4 B_s \tau_{\text{sat}}} .$$

where

$$\beta_e = \frac{(16 \cdot B_s)^2 d}{\pi \cdot \rho \cdot c^2} \quad [\text{CGS}] ,$$

and

$$\beta_r = \left[\alpha(1 + \alpha^2) B_s / \gamma \right] \left(\frac{k}{A} \right)^{1/2} \quad [\text{CGS}] ,$$

where γ is the gyromagnetic ratio, k the anisotropy energy, α the Gilbert damping parameter, and A the exchange stiffness constant.

Calculations⁵ concerning core losses are presented graphically in Fig. B-1.

APPENDIX C: AN EXAMPLE OF PULSE SHARPENING WITH MAGNETIC MATERIALS

One of the tasks to which ferrite is often applied and is ideally suited for is pulse sharpening. This differs from magnetic pulse compression in that the energy in the leading edge of the pulse is not stored but reflected back to the source.

An example of a ferrite pulse sharpener is schematically illustrated in Fig. C-1. We will not go into detail on this subject because it lies outside the scope of this paper.

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Fig. 1

Diagram of a Cascading Saturable Reactor

Fig. 1a Multistage Saturable Reactor

Fig. 1b Operation of a Single Stage

Fig. 2

Typical B-H Curve for a Saturable Core

$$V_L = N \frac{\partial \Phi}{\partial t} = NA \frac{\partial B}{\partial t}$$

$$\therefore \int V_L dt = NA \Delta B$$

Fig. 3

Three Stage Magnetic Pulse Amplifier

$R_{in} - 10^7 \Omega$

$R_{out} - 1.6 \Omega$

$C_1 = C_2 = C_3 - 20 \text{ nf}$

$C_3 = 1.6 \Omega, 3 \text{ ft. Water PFL}$

$L_1 = 32 \text{ turns on } 1 \text{ mil tape Ni}_{50}\text{Fe}_{50} \text{ Core } (9.25" \text{ I.D.} \times 18.5" \text{ O.D.} \times .5" \text{ w})$

$L_2 = 10 \text{ turns on TDK P11 Ferrite Core } (6.75" \text{ I.D.} \times 12.25" \text{ O.D.} \times 1.0" \text{ w})$

$L_3 = 2 \text{ turns on TDK P11 Ferrite Core}$

Fig.4

Representation of the Three Stage Magnetic Switch Operation

Pictorial:

Fig. A-1

Low Field D.C. Magnetic
Properties of Metglass
2826

Energy Dissipation for Various Core Materials

Fig.4 Pulse Duration

① Mild Steel	12.5 μ Ω -cm	$\mu = 2500$	$\Delta B = 3 t$	a) $\frac{1}{2}$ mil
② Si Fe	50 μ Ω -cm	$\mu = 10,000$	$\Delta B = 3 t$	b) 1 mil
③ Ni ₅₀ Fe ₅₀	50 μ Ω -cm	$\mu = 20,000$	$\Delta B = 2.4 t$	c) 2 mil
④ Bi ₂₀ Fe ₈₀	150 μ Ω -cm	$\mu = 20,000$	$\Delta B = 2.4 t$	d) 1"
⑤ Mn Ferrite	20 Ω -cm	$\mu = 1,000$	$\Delta B = 0.5 t$	e) 10"
⑥ Zn Ni Ferrite	10 ⁷ Ω -cm	$\mu = 1,000$	$\Delta B = 0.5 t$	

Fig. C-2

Example of a Ferrite Pulse Sharpener

L_s - 8 turns Ferrite core (6" O.D. x 4" I.D. x 1" W.)

$V_{in} - 20\text{ kV}/\text{div} : 20\text{ ns}/\text{div}$

$V_{out} - 20\text{ kV}/\text{div} : 20\text{ ns}/\text{div}$