A MAGNETICALLY SWITCHED KICKER FOR PROTON EXTRACTION

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Abstract

The application of magnetic current amplification and switching techniques to the generation of precise high current pulses for switching magnets is described. The square loop characteristic of Metglas tape wound cores at high excitation levels provides excellent switching characteristics for microsecond pulses. The rugged and passive nature of this type pulser makes it possible to locate the final stages of amplification at the load for maximum efficiency.

Introduction

With three uniformly spaced beam batches in the Fermilab main ring, extraction for P-bar production may be accomplished with a half sinusoid pulse. A pulsed magnet provides a .45 mrad kick to extract the 120 GEV beam. This requires a peak current of 4.2Ka for extraction at 120GEV which increases to 5.2Ka for 150GEV extraction. The 21Usec revolution frequency necessitates a 7Usec batch to batch spacing.

To meet these modest requirements, a pulsed power supply is required which can develop a 6Ka half sinusoid current pulse with a base width of 10usec into an inductive load of 8uH. An obvious design is to resonantly discharge a capacitor into the inductive load thru series diodes to prevent current reversal. Unfortunately, the recovery time of the diodes is sufficiently long that the stored energy which accumulates in the inductive load during diode recovery will break down the diodes when they finally do turn off. The results of this effect as shown in figure 1 indicate that the diodes drop out of conduction 3Usec after the load current goes through zero. At this time, the load current has reached a level of 1600a. As the diodes recover, the reverse voltage generated by Ldi/dt reaches a peak of 16Kv for this particular case.

The magnetic switch offers an attractive solution to the diode recovery problem and provides the useful side benefit of passive current amplification as well. This technique has seen widespread use in the area of radar modulators since the early 1950's.[1][2][3] The basic principle behind magnetic switching is to utilize the large changes in impedance which occur when a ferromagnetic material is driven into saturation. By using saturable reactors in the transmission line configuration shown in Figure 2A, this behavior can be used to amplify current in a resonant circuit. Multiple stages are used to achieve additional gain. Consider the case where all

capacitors have equal values. When switch S closes, C_o is charged thru L_o until reactor L_1 saturates. C_o then charges C_1 thru L_1 until L_2 saturates and lets C_1
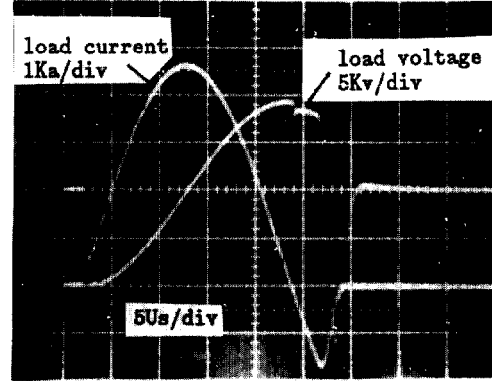

Fig. 1 Effect of diode recovery in a resonant circuit.

charge C_2 thru L_2. The peak current in each of these loops is given by:

$$I_p = V_c/Z_o = V_c \sqrt{C_n/2L_n}$$

where V_c is the peak capacitor voltage. By making the saturated inductance progressively smaller in successive stages, the peak current will increase as the inductance decreases. This is illustrated in Figure 2B.

To examine the circuit in more detail, let us start with Maxwell's equation for time-varying magnetic fields:

$$\oint E \cdot dl = V_L = N \, d\phi/dt = NA \, dB/dt$$

from which:

$$V_L dt = NA(B_s - B_i) = NA\Delta B$$

where N is the number of turns around a core having a magnetic cross-sectional area A. B_s and B_i represent the saturation and initial fields respectively.

The time required to transfer charge from one capacitor to the next is given by:

$$T_t = (L_n C/2)^{1/2}$$

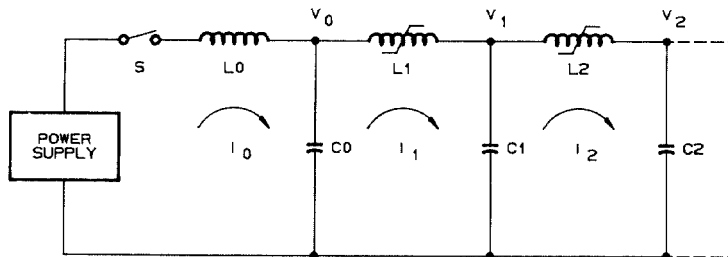where $C_1 = C_2 = C_3 = C$. The time required to transfer charge should be approximately equal to the time to

FIGURE 2A
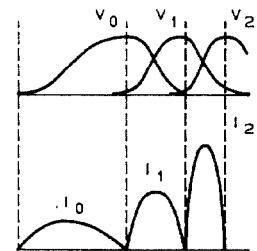

FIGURE 2B

reach saturation in the core. This leads to the relation:

$$T_t = 2(B_s - B_i)NA/V_c$$

where V_c is the capacitor voltage.

The saturable reactor in our design is a coaxial structure for which the inductance is given by:

$$L_s = 2 \times 10^{-7} l_w N^2 . \ln(R_o/R_i)$$

where l_w is the reactor length, R_o and R_i are the outside and inside diameters of the toroidal windings. N is the number of windings on the reactor.

To perform satisfactorily as a switch, the ratio of the unsaturated inductance to the saturated inductance must be greater than 2000.[1] Such a reactor has hysteresis loops similar to those shown in figure 3. Wide flux swings in the core material allows large transfers of energy per pound of core. An abrupt transition between the saturated and unsaturated states produces a correspondingly fast risetime for the switch. Losses and the rounding of the transition into saturation are dependent on dB/dt and the propagation of the domain walls in the ferromagnetic tape.[4 5 6 7 8 9 10] The net effect of these losses is to produce a magnetizing current during the time that the field is changing from B_i to B_s.
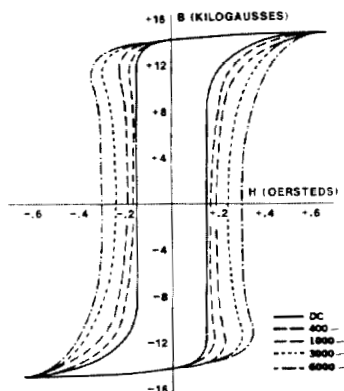

Figure 3 B - H loops for Metglas alloy 2605SC

Toroidal cores for this pulser are made of a .001 inch amorphous alloy 2605SC tape manufactured by Allied Chemical.[11 12] They have an I.D. of 7.35 in., an O.D. of 8.96 in., and a height of 2 in. Twelve cores are used in each reactor. Buildup on the cores was purposely kept low since toroidal cores saturate from the inside out due to the difference in magnetic path length. As portions of the core saturate, the effective area is reduced forcing a higher dB/dt in the remaining unsaturated areas. This can lead to interlamination sparking. The tape is coated with silicon dioxide to achieve an interlamination breakdown rating of of 2 volts per lamination and a packing factor of 75%. Kapton washers provide insulation between adjacent cores. Each saturable reactor is contained in a 10 inch diameter aluminum cylinder filled with transformer oil. The windings are tailored around the core stack to provide a uniform current sheet around the cores.

The initial flux density can be set by flowing a RESET current through an auxiliary winding to magnetize the core in the reverse direction. Such a current may be pulsed or DC, but in either case, it must be decoupled from the switching reactor. For this pulser, chokes are used for decoupling. Their effect is to limit load induced current in the RESET circuit to 12 amps.
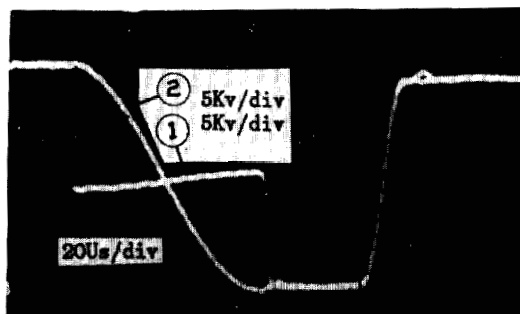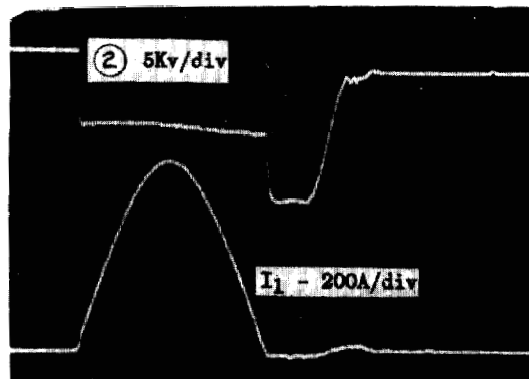

Figure 5

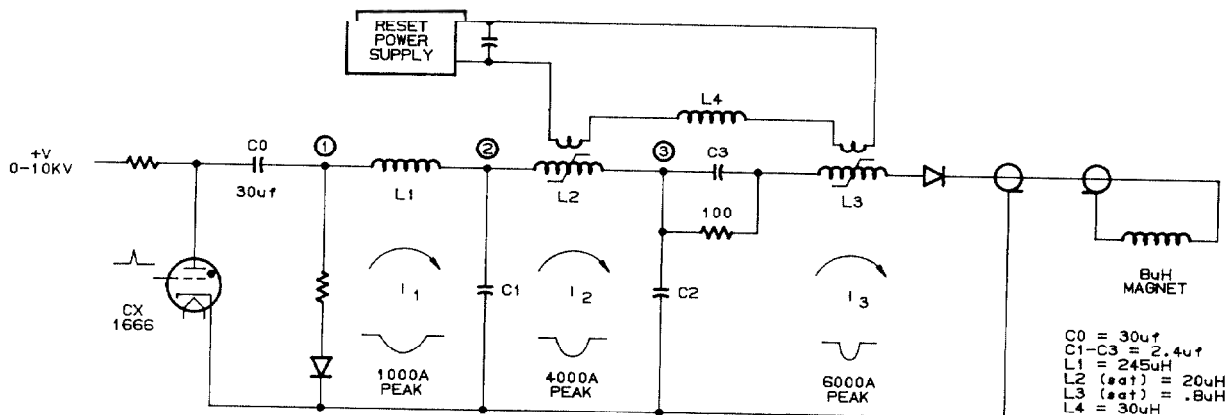Voltage at node 2 and thyratron anode current.
Figure 6

FIGURE 4   MAGNETICALLY SWITCHED PULSER

The magnetically switched pulser is shown in Figure 4. C_o is charged to a maximum of 10Kv. A hydrogen thyratron switches the voltage on C_o across L_o and C_1. Since C_o is much larger than C_1, the final voltage on C_1 is nearly twice the final voltage on C_o. Figure 5 shows typical voltages at nodes 1 and 2 of figure 4. when the current in the loop swings through zero as shown in figure 6, the thyratron turns off and its anode voltage falls to V_{c1} which has a typical minimum of -19Kv. For a 6Ka output pulse, the peak anode current is approximately 950 amps.
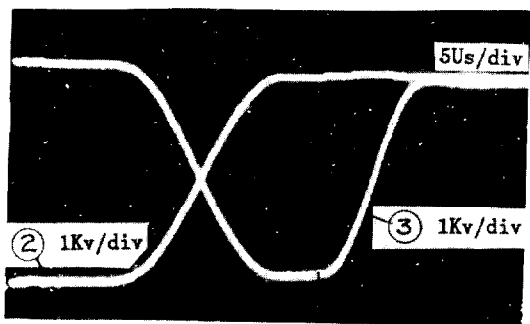

Figure 7

Figure 7 shows the resonant transfer of energy from C_1 to C_2 after L_2 goes into saturation. Figure 8 shows the magnetizing current which occurs during this interval. It appears as a "front porch" on the output current pulse. Following the output pulse, the energy resides as a voltage on C_3 which must be dissipated before the next pulse. To prevent this voltage from saturating the switching cores in the reverse direction, a diode stack is placed in series with the lead. A "rear porch" follows the output pulse while this diode goes thru the recovery process.
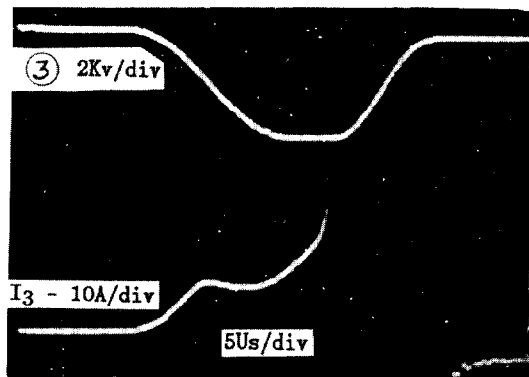

Figure 8

A minimum delay of 85uSec occurs following a trigger pulse during which time resonant charging (70uSec) and compression (15uSec) take place. This delay is a function of the RESET current which sets the peak to peak flux swing in the saturable reactors. While this delay is slightly temperature sensitive, it is relatively jitter free. This delay is amplitude sensitive, however, which requires a timing adjustment for an amplitude change. Such an adjustment could be eliminated by changing the RESET current or providing a feedback loop which would adjust the RESET current to maintain a fixed propagation delay through the system.

A side benefit of this approach is that amplification is carried out by capacitors and inductors which can be placed in the tunnel environment as part of the pulsed load to minimize power losses in otherwise long high current cable runs. Active elements such as the hydrogen thyratron could then be conveniently located some distance away.

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