

THE APPLICATION OF MAGNETIC SWITCHES AS PULSE SOURCES FOR INDUCTION LINACS

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Abstract

Future accelerator requirements of the Particle Beam Program for increased repetition rates and reliability led to the investigation of alternative switching schemes of pulse compression using saturable inductors. This technique has been in use for several decades, but at relatively low power levels and long pulses. Recent developments in amorphous magnetic materials has eased the challenging problem of generating 250 kV pulses for 50 ns at power levels exceeding 20 GW with fast risetime and good efficiency. The timing simultaneity required in linacs from many such parallel systems was achieved with a high degree of voltage regulation and timing feed-forward techniques. The application of magnetic switching has not only exceeded the rep-rate and jitter requirements for short bursts of pulses, but has provided excellent reliability making them applicable for a variety of other high-average power applications besides the Particle Beam Program.

Introduction

The Advanced Test Accelerator (ATA) represents a significant advance in induction linac technology. Its major limitations in performance derive from the use of spark gap switching. Although the ATA systems have been performing quite well throughout the initial operation of this accelerator, it is clear that replacement of the spark gap switches with magnetic switches could result in major improvements in reliability and performance.

Pulse Power Technology

The present technology developed for the ATA deviated considerably from the conventional multi-terawatt pulse power sources that are common throughout the country. Most of those systems are required to provide from a few pulses a day to a few pulses per second. The requirement that made the ATA unique was the need to achieve a ten-pulse burst at one kilohertz specifically to study beam propagation. The rep-rate requirement and the need for reproducibility from pulse to pulse led to the development of a coaxial gas-blown spark gap and power conditioning sources differing from the Marx-type generator widely used in the community. The unique coaxial geometry provided a longer than average life and uniform pulses as the electrodes wore. Existing ATA pulse power will, therefore, provide an adequate technology base for beam propagation experiments.

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Enter Magnetic Pulse Compression

It was clear, however, even at the time of design and construction of the ATA that for higher rep-rates and reliability other switching schemes would have to replace the spark gaps. The existing system is limited to one kilohertz or less for ten pulses, trigger electrodes must be changed every few million shots and 15 horse power are required for each spark gap to blow high-pressure gases. Projecting these requirements for greater than 1 kHz operation or greater energies makes this technology totally impractical.

A scheme which has been around since the 1940's and made popular by Melville in 1951 was re-examined for applicability toward satisfying the future requirements of the Particle Beam Program. The technique of pulse-time compression by using saturable reactors has been used in recent years to generate low-power pulses for radar modulators.

Although fundamentally similar in principle, the requirements for the ATA differed vastly from those of radar modulators. The peak power output requirements were four to five orders of magnitude greater, the voltage one to two orders of magnitude higher and the rise time/pulse width one or two orders of magnitude shorter. The task was further complicated by the necessity to have absolute simultaneity of output pulses from the parallel operation of several hundred pulse generators.

The main driving factor in going to non-linear magnetics was still the requirement for achieving rep-rates (in burst mode) greater than 1 kHz.

On first analysis of non-linear magnetics, it appeared that extrapolation to higher power levels and voltages would be achievable by applying proper techniques. The limitation in rep-rate would be those imposed by the propagation time through the compression stages, the time to reset the cores and the recovery time of the switching devices. The more challenging problem consisted of generating a pulse with good risetime, efficiency and simultaneity of a few nanoseconds from many parallel systems.

Experiments in Magnetic Switching

Although many magnetic pulse generators have been constructed in outside industry and some within the Laboratory, the combined parameters of the ATA made this requirement rather unique. No doubt, considerable advancement to the state-of-the-art would be needed.

The basic circuit for magnetic pulse compression is essentially the same as originally conceived. The principle behind magnetic switching is to use the large changes in permeability exhibited by saturating ferri-(ferro-) magnetic materials to produce large changes in impedance. The standard technique for capitalizing on this behavior is illustrated in Fig. 1. First, one starts with a repetitive power source which utilized existing technology to generate the initial pulse. The pulse then goes through several

states of compression until the desired output is obtained. 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 and limited only by the physical layout and materials properties. The compression process is depicted by Fig. 2 and the operation of this circuit can be described as follows. 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 sat, but since $L_1 \text{ sat} \ll L_0$, C_2 charges more rapidly than C_1 did. This process continues through the successive stages until C_n discharges into the load through the saturated L_n . Each successive saturable reactor is designed so that saturation occurs at the peak of the voltage waveform. The B-H loop on Fig. 3 shows the states of the saturable reactor. Section 1-2 is the active or high-impedance (permeability) region during which time the inductor acts as an open switch; point 2 is reached at the peak of the voltage waveform at which time the core saturates and the inductor becomes a low-impedance (permeability); section 2-4 is the time when the core is reset to its original state ready for the next cycle.

Because "magnetic switches" are actually not switches at all but pulse compressors, they require an initial pulse to work from. We typically achieve this initial pulse by discharging the energy stored in a capacitor (intermediate store) into the magnetic switch. The magnetic switch is designed so that thyratrons can be used in this service. The various methods of achieving high rep-rates are outlined in Fig. 4. While most of our pulsers operate in the simpler command resonant charge mode, the time required to recharge the intermediate storage capacitor combined with thyatron recovery times limits operation to ~15 kHz.

At first glance, it would appear that by adding magnetic pulse compression to a repetitive pulse generator one is adding complexity to the system. It is clear that multistage switches require multiple inductors and capacitive storage units each capable of storing the full pulse energy. Since core volume and capacitor volume vary linearly with pulse energy, going to larger and larger systems means that magnetic switches will be bulky and heavy. The final payoff, however, more than justifies their usage. In fact, there are no other switches available which offer a solution to the problem of high-peak energy (~10 gigawatt), high rep-rate (>10 kHz) and essentially unlimited life. Magnetic switching is the key element in "coupling" a state-of-the-art switching device to an output load and achieve all the ATA parameters. A typical requirement for an accelerator cell is a 70 ns pulse of 250 kV, 40 kA and risetime of 20 ns (10-90%). This corresponds to a rate of rise in current (di/dt) of 10^{12} A/sec and a peak energy of 10 gigawatts. A typical state-of-the-art switching device which can operate at burst frequencies >10 kHz is the thyatron. The voltage rating of about 30 kV, current rating of 10 kA with a limit in di/dt of 10^{10} A/sec corresponds to a peak power of 0.3 gigawatts. The limits imposed by the switching device usually leads to paralleling of several units and to a magnetic switch which differs slightly from the conventional one depicted in Fig. 1.

Over the past two years, magnetic pulse generators have undergone considerable evolution. The first device which was built as a demonstration of principle utilized available leftover magnetic materials of Nickel-Iron and ferrite disks from the

ETA. Even under non-optimum design the agreement between theory and experiments was quite good. With the confidence gained from the performance of the small scale magnetic switch, a large one to satisfy the energy levels of ETA was constructed. This experiment not only provided confirmation of the scaling laws, but provided the opportunity to test a low-loss magnetic material with great potential for generating short pulses with good risetime. More will be said about this material in a later discussion. Much was learned about the general problems with going to larger and larger systems. Subsequently, several other magnetic pulse generators have been constructed, tested and installed on both ETA and ATA. Specifically, the grid pulse, the cold-cathode driver and the master trigger on both the ETA and ATA are magnetic pulse generators (Fig. 6) with millions of shots of flawless operation. These systems have undergone improvements in efficiency, simplification of components layout, reduction in number of stages and a prototype has been constructed which is a direct replacement of two ATA pulse power units.

The ATA Upgrade Prototype

The unit shown in Fig. 7 is a replacement for two resonant transformers, two gas-blown spark gaps and two Blumlein lines. Besides being cost effective, it provides performance which is unattainable with any other system.

The brief outline presented in Fig. 5 partially documents the capabilities demonstrated by this prototype.

Simplified schematics of both the existing pulse power units and the prototype magnetic replacement are presented in Fig. 6.

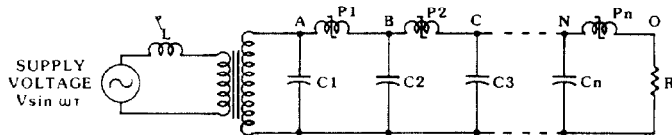
The addition of coupling transformers at both the input and the output of the magnetic pulse compressor add versatility to the system by allowing the operation of the compression stages and the input switching device at their most efficient voltage and current parameters and still achieve the desired output pulse.

This unit is the same diameter as the existing spark gap based system and only slightly longer. It consists of an input step-up transformer, one stage of compression which charges the transmission line, the final stage of compression and the output coupling transformer. The output transformer can be housed as part of the magnetic pulse generator or as part of the load for best impedance matching.

The pulse shaping hardware has evolved to the point where the transformer turns and the interstage capacitors are designed as an integral part of the system. The end result is a magnetic switch which is simple, extremely reliable and satisfies all the required parameters.

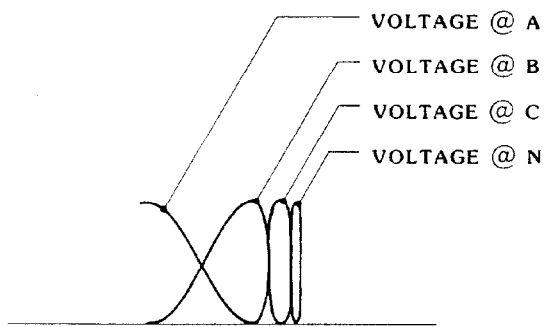
The output from the magnetic driver is transported down to the vicinity of the accelerator cells via two 4Ω , semirigid, water transmission lines. There a pulse transformer provides a 3:1 voltage step-up and a ferrite sharpener steepens the risetime.

A desire to increase the individual accelerator cell voltage from ~250 kV to ~500 kV dictated this procedure. The use of step-up transformers in the accelerator tunnel seemed infinitely preferable to transporting the actual cell voltage.



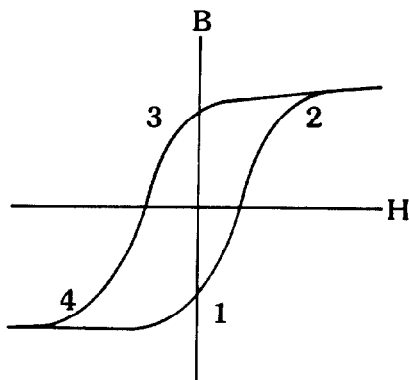
SIMPLIFIED SCHEMATIC OF A MAGNETIC PULSE COMPRESSOR

FIG.1



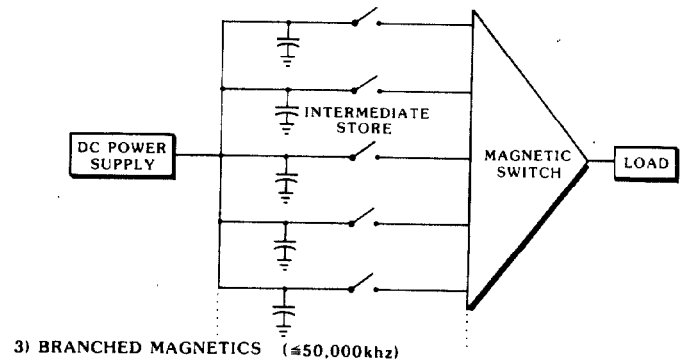
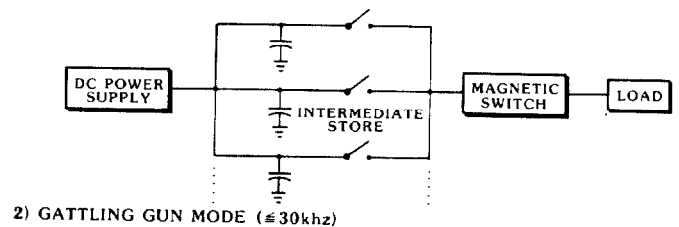
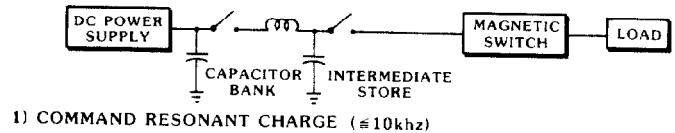
TYPICAL VOLTAGE WAVEFORMS ASSOCIATED WITH A MAGNETIC PULSE COMPRESSOR

FIG.2



B-H LOOP OF A SATURABLE MAGNETIC MATERIAL

FIG.3



THREE MODES OF OPERATION FOR MAGNETIC SWITCHES

FIG.4

OUTPUT PULSE PARAMETERS :

- PEAK OUTPUT POWER 10^{10} WATTS
- PULSE RISETIME @ CELL 15ns (10%-90%)
- PULSE LENGTH 80ns FWHM
- PULSE ENERGY 800J
- EFFICIENCY 80%
- VOLTAGE (2 CELL DRIVER) 300kv @ 18ka/CELL
- VOLTAGE (1 CELL DRIVER) 450kv @ 25ka/CELL
- PULSE TO PULSE JITTER 1/2ns @ ≅ 1kHz
- PEAK BURST RATE (5 PULSES) 15kHz
- PEAK AVG. REPETITION RATE 1kHz @ 10% DF

MAG-1 ATA UPGRADE PROTOTYPE

FIG.5

The output pulse from the magnetic driver and the resulting accelerator cell voltage waveform are shown in Fig. 8. The cell voltage waveform has been shortened due to the saturation of the ferrite which makes up the induction cell core. These cells, currently operated at 250 kV for 50 ns, will require a modification if operation at 500 kV per cell is desired. This modification will probably entail the replacement of the ferrite core with one wound from metglass.

Metglass

In low rep-rate systems, the overall efficiency of the magnetic pulse compression stages is not critical. Even the original pulse compressors which were built from available leftover materials of Ni-Fe and ferrite achieved efficiencies of over 50%. The most critical aspect of the magnetic switch in terms of achieving high efficiency and fast risetimes as well, is the material in the final stages. The material which satisfied all of the requirements was the ferromagnetic metallic glass or amorphous material. The rebirth of the pulse compression technique as a very high power, high rep-rate and high reliability pulse source is due in no small way to this new material. Amorphous materials offer all the required properties of high saturation, high squareness and high resistivity that make the magnetic switch so attractive.

The more recently constructed magnetic switches utilizing this material achieve efficiencies greater than 80%. Commercial availability of this material at about the time when magnetic switching was resurgent also made it very practical. Current production of commercial quantities are achieved by forcing a thin stream of liquid metal into close contact with a moving, chilled metal substrate. To achieve the required cooling rate of 10^6 degree K/sec the ribbon is produced at very high rates and is automatically thin (1 mil). Most of the material used in the magnetic switches has been produced by Allied Corporation under their registered trademark for amorphous alloys called METGLAS. The type of METGLAS used has been mainly the 2605 SC which is iron-based and 2605 CO which substitutes cobalt for some of the iron and yields a higher saturation flux.

For short pulses, the dominant factor contributing to core losses are the eddy currents. Applying saturation wave theory to a section of magnetic tape, it was established long ago that eddy current losses scale as the square of the tape thickness and inversely as the resistivity. The fact that amorphous metals have resistivities about three times higher than those of crystalline alloys and can be mass produced in ribbon of $<28 \mu\text{m}$ thickness makes them ideal for generating fast pulses with high efficiency.

Going to Higher Rep-Rates

The type of magnetic pulse generator discussed so far consisted of a repetitive pulse source and several serial stages of pulse compression. Such a system can supply a burst with any number of pulses or can operate continuously. The burst rate, as already mentioned, is established by thyatron recovery times. If, however, the requirements are for a fixed number of pulses in a burst then a new scheme of pulse generation becomes feasible. This scheme pictured in Fig. 4 involves a number of parallel energy storage capacitors and switches which are fired in sequence at practically any rep-rate. The circuit for such a magnetic burst generator which is self-resetting between pulses is shown in Fig. 9.

Here portions of the eight forward pulses are used to reset the saturable inductors in the circuit. This eight pulse burst generator is essentially a two stage magnetic compressor with eight first stages and four second stages all feeding into one output load.

The timing between the output pulses is simply determined by the time delay between triggering the successive SCR's.

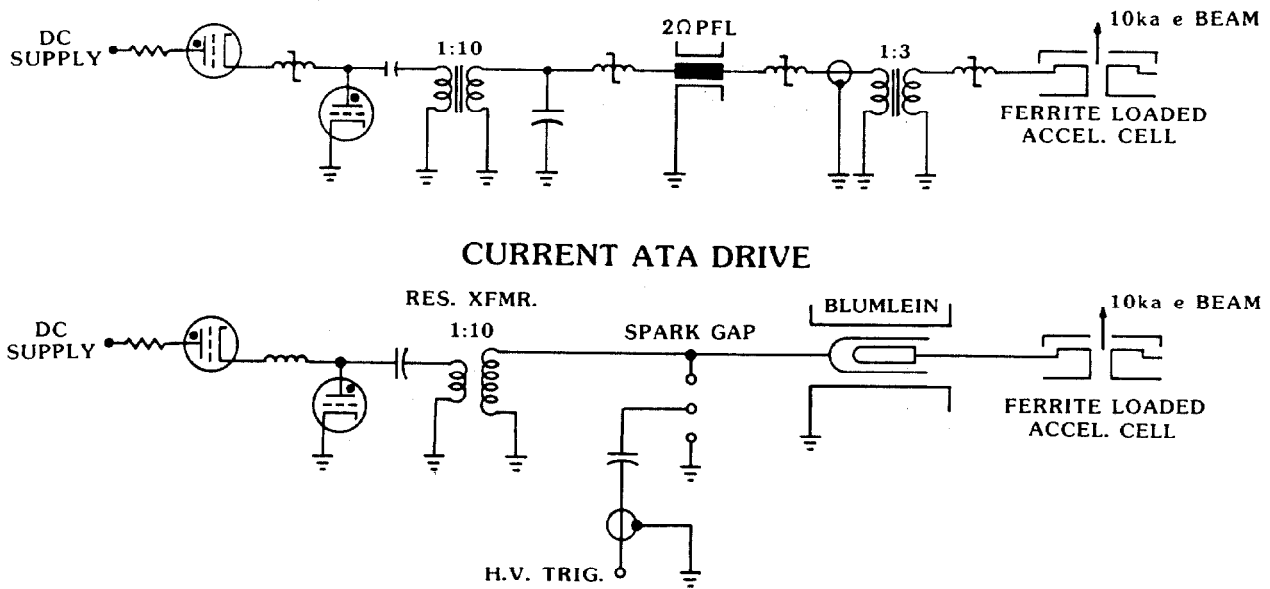
The actual output capacitors C_{2n} consisted of varying lengths of RG58. The timing delays between the triggering of the SCR's was determined by cable lengths. Fig. 10 shows the summed output pulse from a 60 ns length of cable. The eight pulse burst has a rep-rate of up to 16 MHz.

While this initial proof of principle experiment was performed at low power, it appears that this technique of burst generation offers a way to build high power pulse generators with essentially unlimited rep-rate.

Conclusion

The coupling of an old technology of pulse compression with a new magnetic material has resulted in the development of a pulse power system which exceeds future needs of the Particle Beam Program. The addition of a high peak power switch to initiate the compression chain has allowed the reduction of the total number of stages producing a simpler, higher efficiency magnetic pulse generator. The higher efficiency has now made continuous operation of induction accelerators with extremely high average power a real possibility. The rep-rate limitation was not in the magnetics portion of the generator but was imposed by the recovery time of the initial pulsing device (thyatron). In fact, a new magnetic "burst" generator was developed which magnetically isolated the recovery time of the switching device allowing practically unlimited rep-rates. In conclusion, magnetic pulse generators are ideally suited for driving low impedance induction accelerators with short pulses (70 ns), short risetime (15 ns), high peak power (10 gigawatt) at any rep-rate.

INDUCTION LINAC NONLINEAR MAGNETIC DRIVE



SIMPLIFIED SCHEMATICS OF THE EXISTING ATA PULSE POWER CHAIN & THE NONLINEAR MAGNETIC DRIVE PROPOSED FOR AN UPGRADE

FIG.6

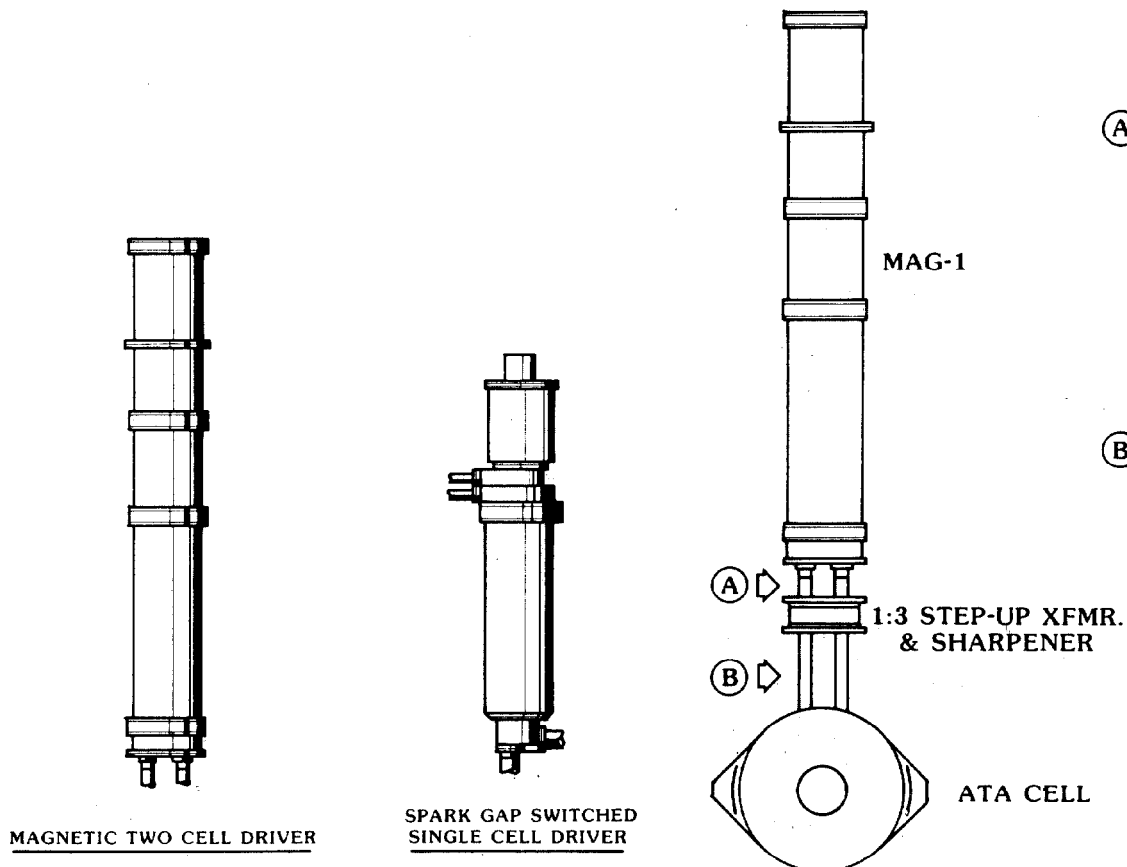
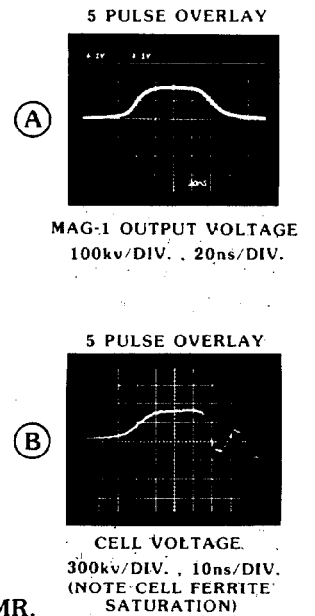
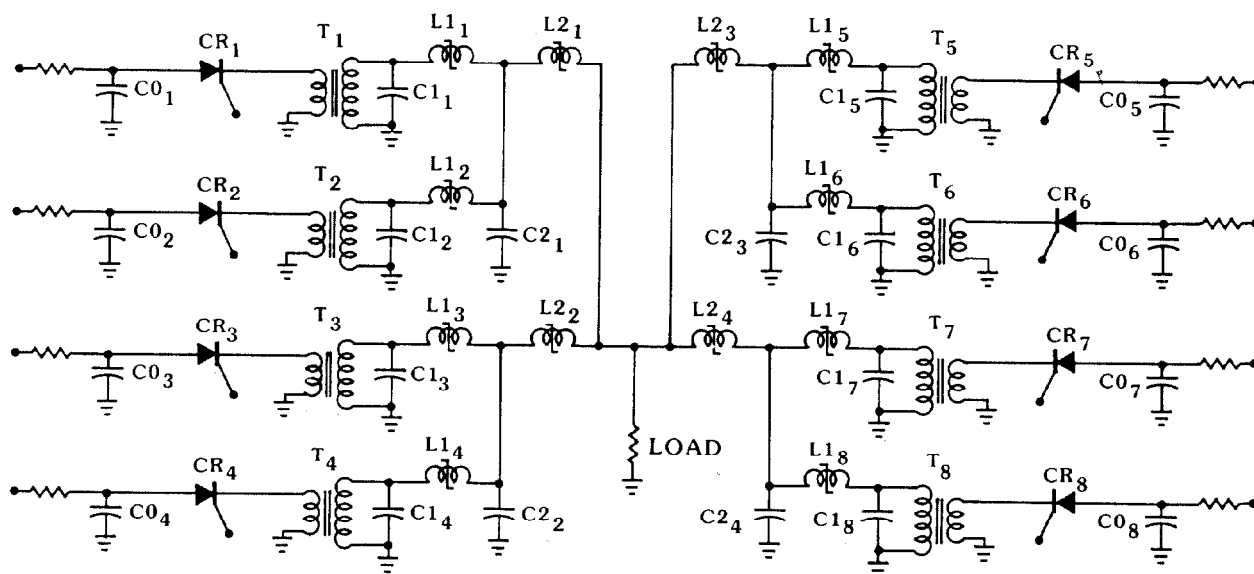


FIG.7



MAG-1 (ATA UPGRADE PROTOTYPE) INITIAL TESTS INTO ATA ACCEL. CELL

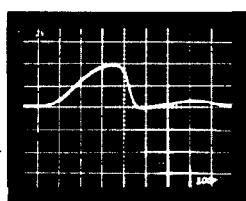
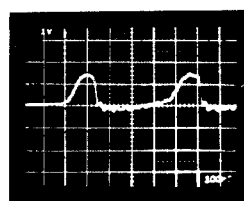
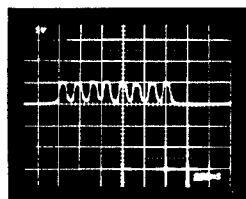
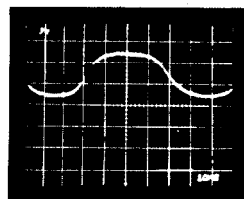
FIG.8



EIGHT PULSE BURST GENERATOR

FIG.9

- 70 VOLT CHARGE OF $C0_N$
- 120ns DELAYS BETWEEN SCR TRIGGERS
- FIRING SEQUENCE: 1-3-5-7-2-4-6-8

VOLTAGE ON $C1_N$
1kv/DIV. , 100ns/DIV.VOLTAGE ON $C2_N$
(2 X 15ns RG-58)OUTPUT PULSE
625v/DIV. , 100ns/DIV.OUTPUT PULSE
250v/DIV. , 100ns/DIV.

TYPICAL WAVEFORMS

FIG.10