Pulsed Magnet System for Production of High Magnetic Fields[1]

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In recent years there has been considerable interest in the production of high magnetic fields. Much work involving high magnetic fields is in progress in nuclear, plasma and solid state physics. A pulsed magnet system has been constructed at Oklahoma State University to furnish high magnetic fields. The pulsed magnet system has been successfully used in the investigation of high-field magnetoresistance in semiconducting diamond (Russell and Leivo, 1965) and will be used in future solid state experiments. In particular, it was designed for infrared cyclotron resonance experiments in solids. The magnet system provides up to 45 kilojoules of stored energy for producing the magnetic fields.

The high magnetic fields are obtained by discharging a bank of capacitors through an electromagnet. Several different magnets have been tested each of which falls into one of the three following classes:

1) The magnet coil is constructed of a beryllium-copper alloy and is in the form of a continous helix turned from a solid bar. The coil is clamped between two thick endplates, and, to further enhance the strength, the space around the coil between the endplates is filled with a cement (epoxy, Sauereisen, or calcium aluminate). Similar magnets have been described by others (Foner & Kolm, 1957). The highest magnetic fields were obtained with this type of construction. Fig. 1 shows a magnet of this type. In the magnet shown the end-

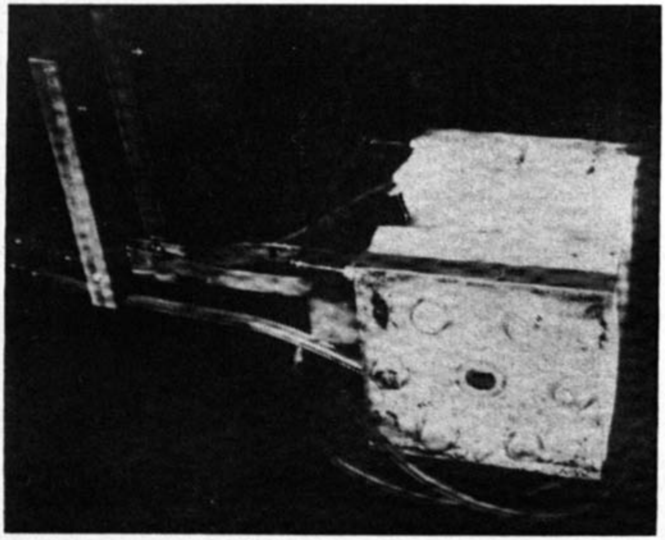

Fig. 1 Helical coil magnet

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plates were of stainless steel and were insulated from the coil. Magnetic fields up to 400 kilogauss were obtained with the magnet.

2) The magnet (Fig. 2) is of the flux concentrator type and has its primary winding embedded in the brass flux concentrator body which is shaped to enhance the field at the center. The method has been described elsewhere (Howland and Foner, 1962) and is between the first and third types in production of magnetic field strength.

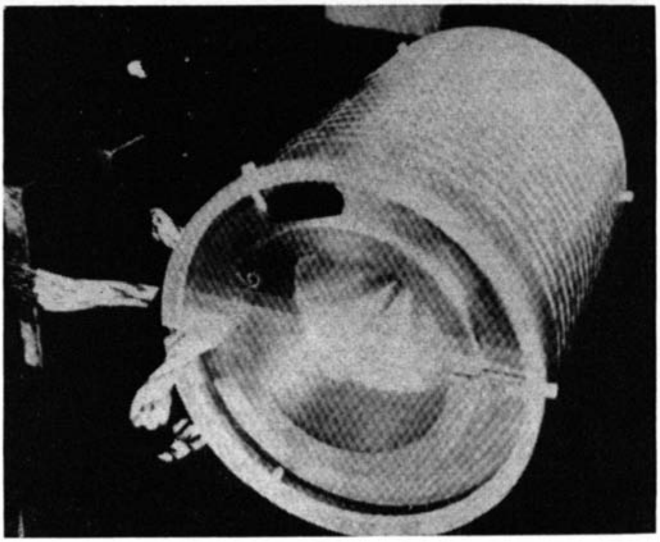


Fig. 2 Flux concentrator magnet

3) The magnet is a multilayer coil of wire wound on an insulating mandrel. The wires are held in place by being coated with an epoxy cement during the winding process and by wrapping several layers of epoxy-impregnated fiberglass material around the coil. The magnet can easily be made to give very long period discharges. Fig. 3 shows a magnet of this type. The magnet gave over 100 discharges of 170 kilogauss peak magnetic field.

The pulsed magnetic fields were measured by integrating the output of a search coil inserted in the magnetic field. The integrated output was then displayed on an oscilloscope.

Fig. 4 shows a block diagram of the capacitive energy storage system. The system is composed of the capacitor bank together with associated charging and switching circuits. To produce a magnetic field the capacitor bank is charged to the desired difference in potential and then discharged into the load. With the crowbar circuit inoperative, the resulting discharge current through the electromagnet will have the time variation shown in Fig. 5a. The crowbar circuit is used to limit the energy dissipated in the magnet since the resulting heating may be objectionable because of sample heating or magnet deterioration. The current pulse is limited by closing the crowbar switch at point A on the curve, Fig. 5a, and the resulting time variation of the current is essentially as shown in Fig. 5b.

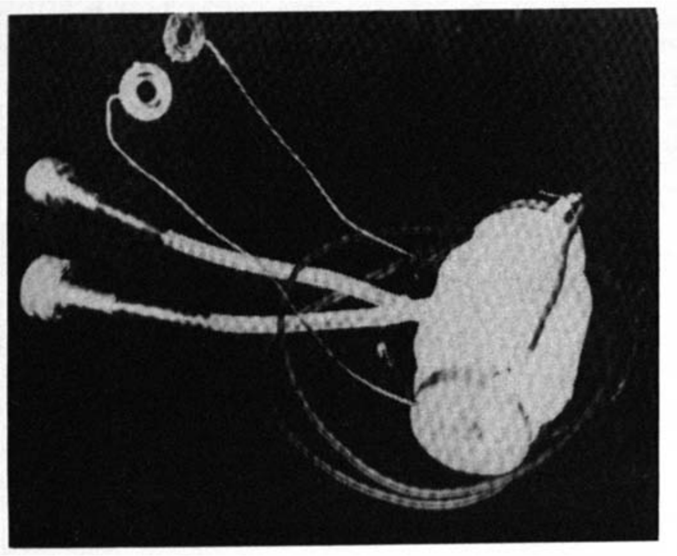


Fig. 3 Wire wound magnet

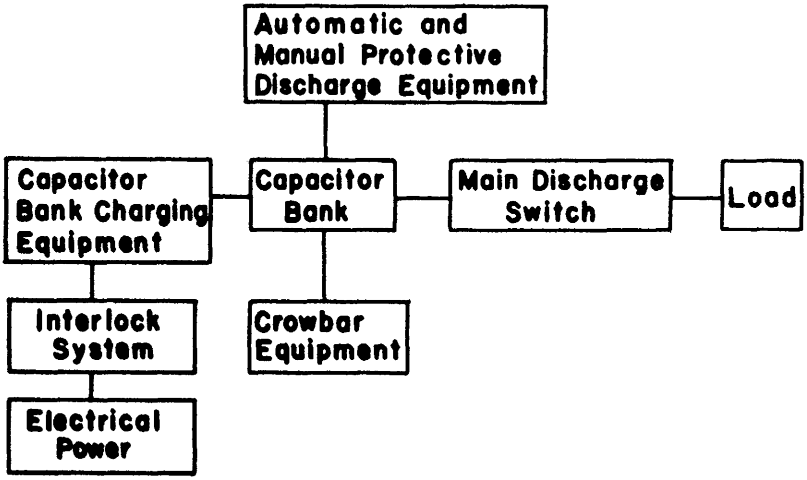
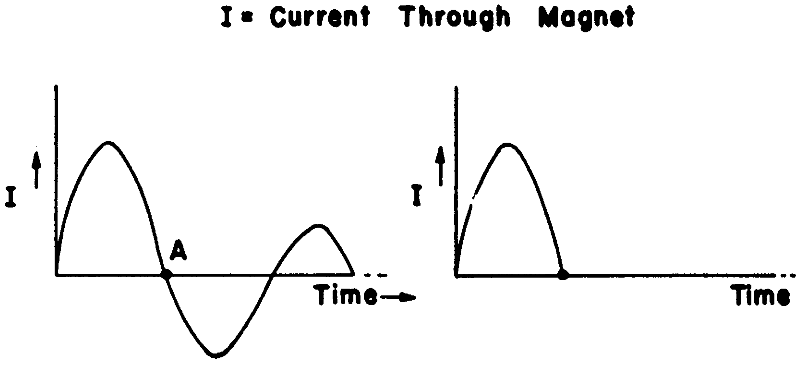


Fig. 4 Block diagram of pulsed magnet system

To more fully describe the capacitive energy storage system consider it to be divided into four parts: 1) bank circuit, 2) bank-charging circuit, 3) crowbar circuit, 4) sequence control circuit.

First consider the bank circuit illustrated in Fig. 6. The capacitor bank is composed of fourteen energy storage capacitors of extended foil construction connected so they may be discharged in parallel. The capacitors are 180-microfarad, 6000-volt units, which, in parallel, give a total



a) Uncrowbarred b) Crowbarred

Fig. 5 Magnet current versus time

capacitance of 2520 microfarads and a maximum total stored energy of 45,360 joules. The equivalent series inductance of each capacitor is less than one microhenry, thus allowing efficient use of the bank with low inductance loads. Fourteen ignitrons, V_4 through V_{17}, one mounted on top of each capacitor, discharge the capacitor bank into the load. The simultaneous firing of the 14 ignitrons is accomplished by the discharge of the small energy storage capacitor, C_3, through the ignitors of the 14 ignitrons. This discharge is initiated by a signal received at A from the sequence control circuits. The signal causes the blocking oscillator to produce a firing pulse for the hydrogen thyratron, V_2, which then discharges C_3 through the ignitor of V_3 which then simultaneously fires the 14 ignitrons.

The capacitor bank and the trigger capacitors are charged by equipment in the bank-charging circuit shown in Fig. 7. The capacitor bank is charged by the three-phase full-wave bridge power supply which furnishes a variable output voltage from 0 to over 6500 volts by the three-phase variable autotransformer, T_3, in the primary circuit of the high voltage transformer, T_4. The operation of the power supply is controlled by contactor K_1 which operates upon a signal from the sequence control circuit. The power supply is capable of charging the capacitor bank to full rated potential in 18 seconds, thus allowing rapid repetition of experiments and keeping small the time the bank is charged. The trigger capacitors, C_3 and C_{28}, are charged by the two single-phase full-wave bridge power supplies. Two Schmitt trigger circuits are used to monitor the bank voltage. One of the circuits is used to stop the charging of the bank when a preset potential level is reached, and the other is used to prevent the bank from being overcharged.

The ignitron tubes, V_4 through V_{17}, used for discharging the capacitor bank into the load lose their rectifying properties for the currents and pulse times associated with magnets of the first type and thus become closed switches conducting equally well in both forward and reverse directions. As stated previously, the crowbar circuit shown in Fig. 8 stops the current through the magnet after approximately one-half cycle. The crowbar circuit, as used in this application, provides a low impedance current path in parallel with the electromagnet after approximately one-half cycle of magnetic field oscillation has taken place. Referring to Figs. 6 and 8, the crowbar circuit shorts the bank through crowbar re-

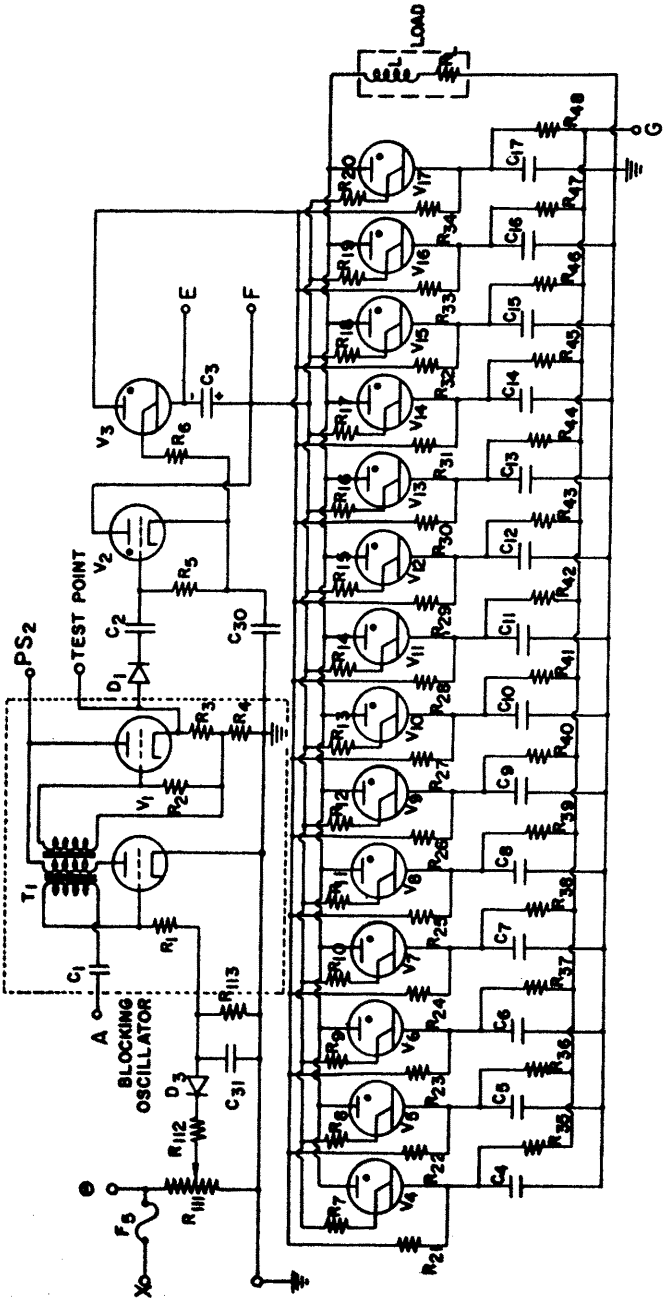


Fig. 6 Bank circuit

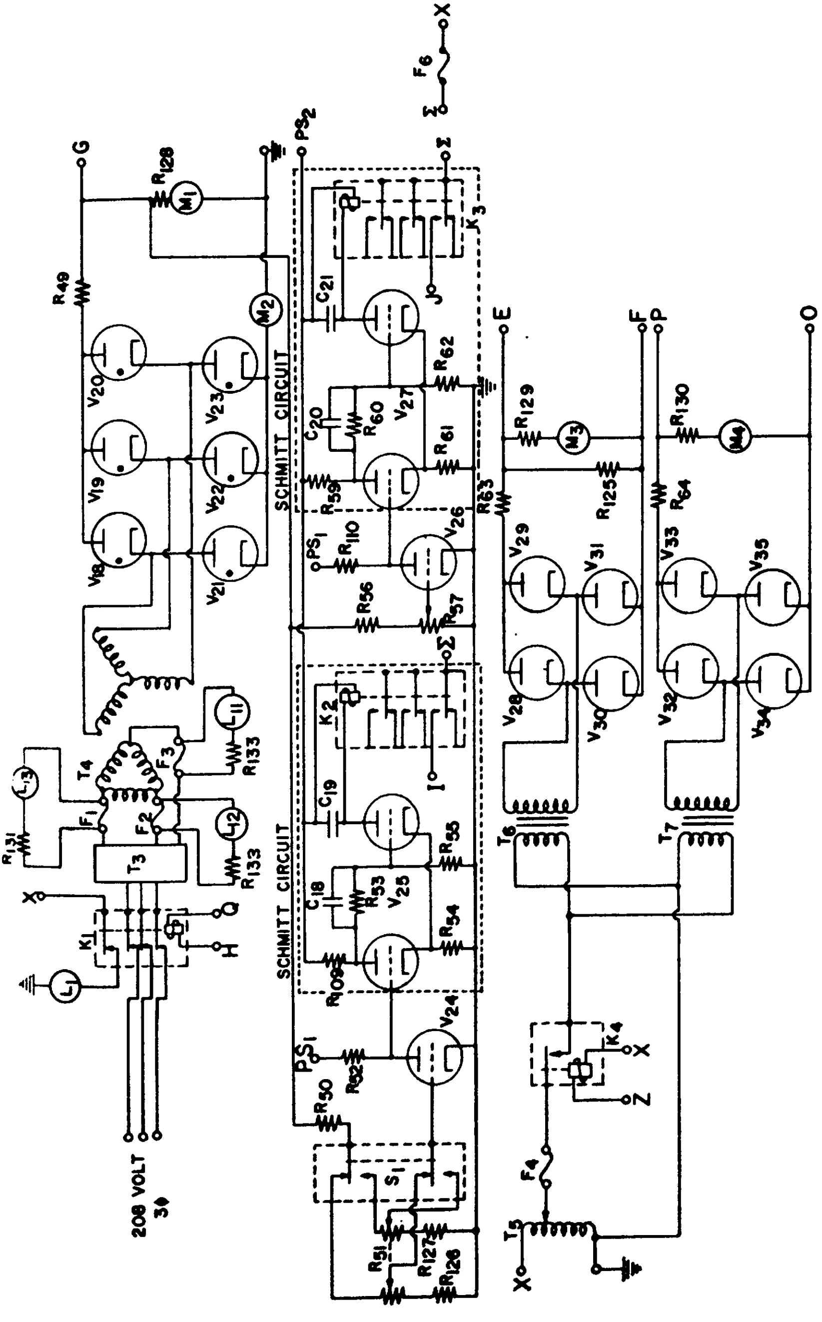


Fig. 7 Bank-charging and voltage-sensing circuit

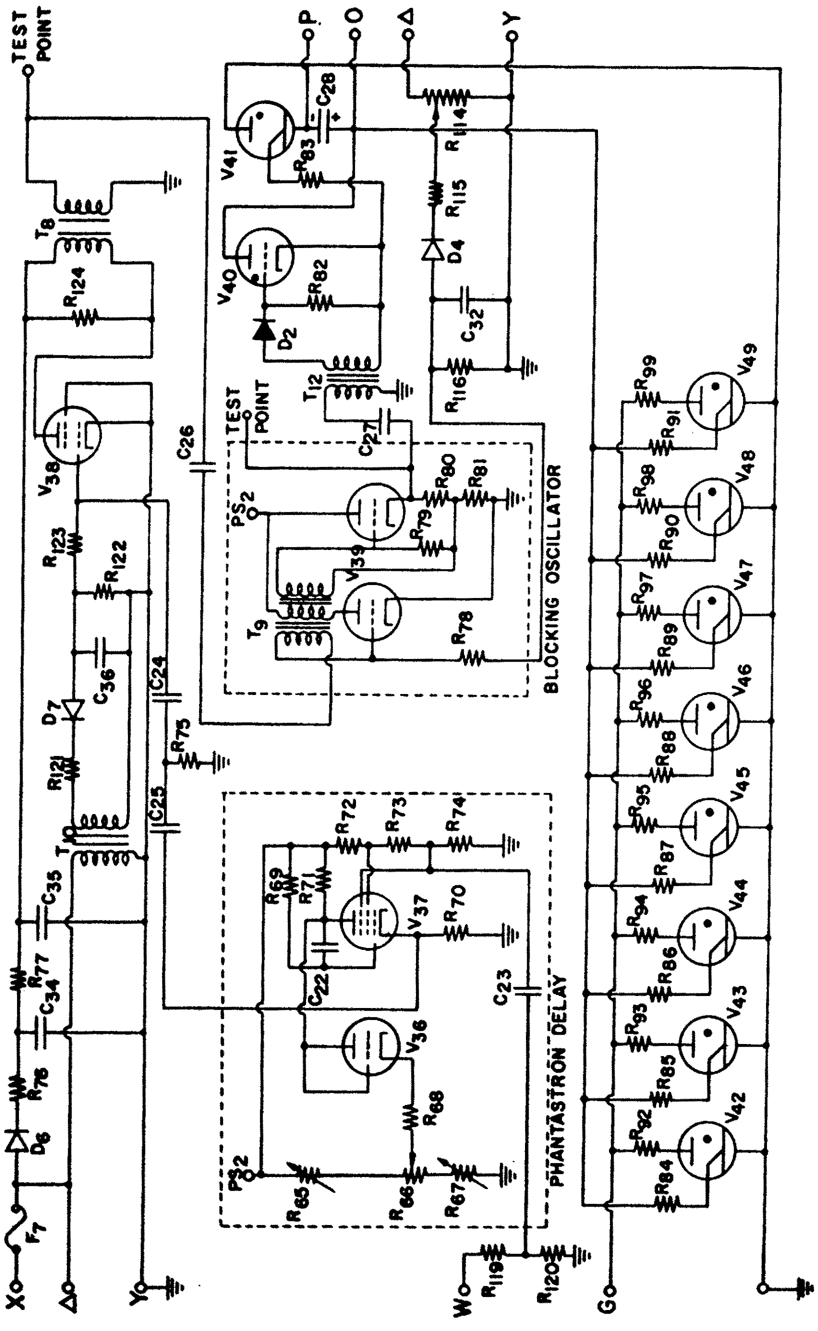


Fig. 8 Crowbar circuit

sistors R_{38} through R_{45} and R_{52} through R_{59} by means of ignitron tubes V_{42} through V_{49}. The ignitrons V_{42} through V_{49} are simultaneously fired in the same manner as those used in discharging the bank. In this case, however, the firing signal travels through a delay circuit which delays the firing of V_{42} through V_{49} until the proper time. The delay circuit consists of a phantastron delay followed by a differentiating and pulse-forming circuit. The delay is adjustable so the crowbar circuit may be used with magnet coils giving different periods of oscillation.

The operation of the capacitor bank is controlled by the sequence control circuit, Fig. 9. Terminals H and Q are connected to the operating coil of the relay, K_1, which furnishes power to the charging equipment. Therefore, the operation of the capacitor bank-charging circuit is controlled by relays K_5, K_6 and K_7, and switch S_2. Relays K_6 and K_7 are connected to the Schmitt trigger circuits, Fig. 7, and shut off power to the charging equipment when the desired voltage or an overvoltage is present on the bank. Relay K_8 is conecnted so as to be self-energizing when the charge-start push button, S_7, is pressed. Switch S_2 is a charge-halting switch which, when operated, cuts power to the charging circuits and discharges the capacitor bank through resistor R_{104} and the trigger capacitors through resistors $R_{100}$and R_{102}. These resistors are used to 1) furnish an alternative means of discharging the bank, 2) bleed off the remaining bank energy after a normal discharge (un-crowbarred or crowbarred discharge through the load). Two different modes of operation of the capacitor bank may be selected by means of switch S_8. The circuit diagram, Fig. 9, shows switch S_8 in position for the automatic mode of operation. In this mode, after the desired capacitor bank potential has been set on R_{61} and S_1, Fig. 7, switch S_7 may be operated, thus causing the capacitor bank to be charged to the preset potential and then to discharge automatically through the load. The alternate position of switch S_8 selects the manual mode of operation. In this mode when switch S_7 is pressed, the capacitor bank is charged to the preset potential, power to the bank-charging circuit is cut off and power is supplied to the time-delay relay K_{13}. At any time within the next three minutes switch S_9 may be pressed, thus discharging the bank. If the bank is not discharged at the end of the three-minute period, the time-delay relay K_{13} automatically discharges the bank and the trigger capacitors through R_{104} and R_{100} and R_{102} respectively. The bank can be discharged manually through R_{106}, and the trigger capacitors can be discharged manually through R_{101} and R_{103} by operating switches S_3, S_4 and S_5. Switch S_{12} may be used to manually stop the charging of the bank without discharging it. The pulse needed to initiate the action of the blocking oscillator in Fig. 6 and the phantastron delay circuit in Fig. 8 is obtained by furnishing power to the input of transformer T_{11}.

Table I lists the components used in the pulsed magnet system.

The capacitor bank is enclosed in a masonry room for safety. Each capacitor is connected by a RG-19 coaxial cable to a collector plate located outside the capacitor bank room. The magnet is then connected to the collector plate. Ear protection is worn during the operation of the capacitor bank in case there is a failure of the magnet or collector plate insulation.

Although this paper is concerned with the design, operation, and performance of the pulsed magnet system, it is of interest to know whether experiments in pulsed fields can be carried out successfully. There are, of course problems in making electrical measurements during the discharge of the system because of large electrical and electromagnetic disturbances. In general, it is possible to subtract the effects of the system from the desired signal. For instance, the high field magnetoresistance measurements in semiconducting diamond which were previously mentioned were quite reproducible, and at lower fields where measurements could be made with dc magnets the results were identical.

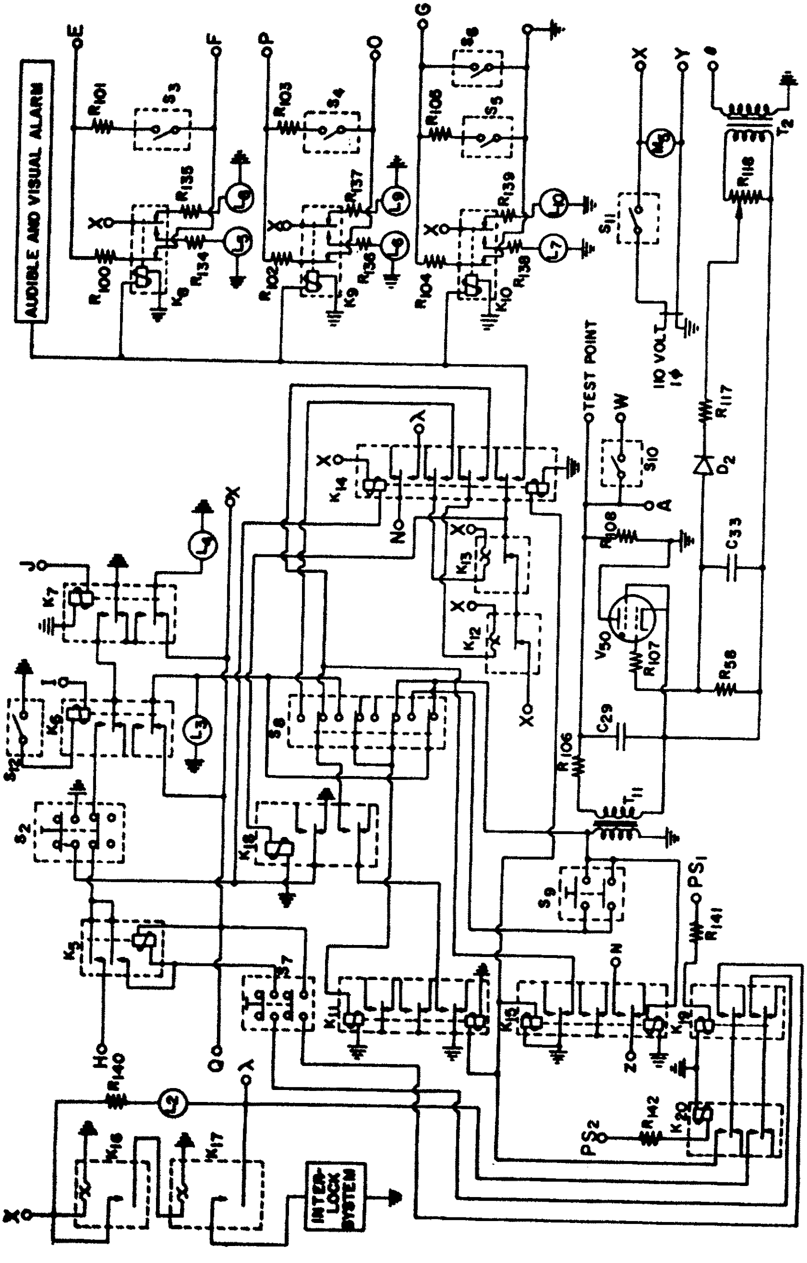


Fig. 9 Sequence control circuits

TABLE I. PULSED MAGNET SYSTEM COMPONENTS LIST

Resistors & Potentiometers			Capacitors		
R_1	20k-ohms	1w	C_1	.05μf	400VDC
R_2	2.7k	½w	C_2	.01μf	10KVDC
R_3	300	½w	C_3	50μf	3,500VDC
R_4	820	1w	C_4 to C_{17}	180μf	6,000VDC
R_5	20k	1w	C_{18}	20$\mu\mu$f	300VDC
R_6	12	2w	C_{19}	0.1μf	400VDC
R_7 to R_{30}	5.6	2w	C_{20}	20$\mu\mu$f	300VDC
R_{31} to R_{34}	6.2	2w	C_{21}	0.1μf	400VDC
R_{35} to R_{48}	.0778	Special Res.	C_{22}	1,500$\mu\mu$f	300VDC
R_{49}	4.17k	2.4kw	C_{23}	3,300$\mu\mu$f	500VDC
R_{50}	5meg	8w	C_{24}	.05μf	400VDC
R_{51}	50k,500k Pot (dual)	½w	C_{25}	500$\mu\mu$f	500VDC
R_{52}	20k	1w	C_{26}	.05μf	400VDC
R_{53}	100k	½w	C_{27}	.1μf	400VDC
R_{54}	15k	½w	C_{28}	20μf	3,500VDC
R_{55}	64k	½w	C_{29}	.02μf	200VDC
R_{56}	5meg	8w	C_{30}	.01μf	10KVDC
R_{57}	75k	2w	C_{31},C_{32}	10μf	150VDCW electrolytic

TABLE I (Continued)

R_{58}	100k	½w	C_{23}	25μf	6VDCW electrolytic	
R_{59}	10k	½w	C_{24}	10μf	150VDCW electrolytic	
R_{60}	100k	½w	C_{25}	.02μf	200VDCW	
R_{61}	15k	½w	C_{26}	25μf	6VDCW electrolytic	
			SWITCHES			
R_{62}	62k	½w	S_1	2PDT	250V	3A
R_{63},R_{64}	25k	100w	S_2	2PDT	110V	10A
R_{65}	10k Pot.	5w	S_3,S_4	1PST Special	3,500V	1A
R_{66}	20k	10-turn linear Pot.	S_5,S_6	1PST Special	6,000V	10A
R_{67}	10k Pot.	5w	S_7	2PDT	110V	10A
R_{68}	22k	½w	S_8	4PDT	110V	3A
R_{69}	1meg	½w	S_9	2PST	110V	½A
R_{70}	3.3k	½w	S_{10}	1PST	250V	3A
R_{71}	1meg	½w	S_{11}	2PST	110V	25A
R_{72}	47k	½w	S_{12}	1PST	250V	3A
R_{73}	22k	½w	TUBES			
R_{74}	2.2k	½w	V_1		6SN7	
R_{75}	56k	½w	V_2		6268	
R_{76}	150	2w	V_3 to V_{17}		G1-7703	
R_{77}	100k	½w	V_{18} to V_{23}		G1-872A	

TABLE I (Continued)

R_{78}	20k	1w	V_{24}		6AS7-GA	
R_{79}	2.7k	½w	V_{25}		5965	
R_{80}	300	½w	V_{26}		6AS7-GA	
R_{81}	820	1w	V_{27}		5965	
R_{82}	2.5k	1w	V_{28} to V_{35}		8020	
R_{83} to R_{91}	12	2w	V_{36}		5814	
R_{92} to R_{99}	.0444	Special Res.	V_{37}		5725	
R_{100} to R_{103}	25k	100w	V_{38}		5727	
R_{104},R_{105}	1.43k	2.8kw	V_{39}		6SN7	
R_{106}	100k	½w	V_{40}		6268	
R_{107}	100k	½w	V_{41} to V_{49}		G1-7703	
R_{108}	51	1w	V_{50}		5727	
R_{109}	10k	½w	TRANSFORMERS			
R_{110}	20k	1w	T_1	300V	1-1-1	pulse
R_{111}	10k Pot.	5w	T_2	115V to 2.5V		
R_{112}	150	2w	T_3	240V	3 phase	9.7KVA variable auto-transformer
R_{113}	100k	½w	T_4	3-5KVA, 4,800-120/240V transformers connected for 3-phase operation		

TABLE I, (Continued)

R_{124}	10k Pot.	5w	T_5	120V	2.3KVA	variable auto-transformer
R_{125}	150	2w	T_6	115V to 3000V at 350ma.		10KV insulation
R_{126}	100k	½w	T_7	120V to 1,900V		.7KVA
R_{127}	10	1w	T_8, T_9	300V	1-1-1	pulse
R_{128}	10k Pot.	5w	T_{10}	115V to 2.5V		
R_{129}	1500	½w	T_{11}	115V	35VA	isolation
R_{130}	510	½w	T_{12}	2000V	1-2-1	pulse
R_{131}	10	1w		METERS	DIODES	
R_{132}	1.5k	½w	M_1	0-7,500 VDC	D_1, D_2	3,000 PIV, 750 ma.
R_{133}	100k	½	M_2	0-3.0 ADC	D_3 to D_7	200 PIV 750 ma.
R_{134}	51	½w	M_3, M_4	0-5,000 VDC		
R_{135}	350k	75w	M_5	0-99,999.9 hrs		
R_{136}	75k	½w		PANEL LIGHTS		
R_{137}	30k	1w	L_1	Red Jewel	1"	
R_{138}	7.5meg	15w	L_2	Red Jewel	½"	

TABLE I, (Continued)

R_{130}, R_{131}	5meg		10w	L_3	Green Jewel	1"
R_{132} to R_{133}	1k		25w	L_4	Amber Jewel	1"
R_{134} to R_{140}	700		20w	L_5 to L_7	Red Indicator	
R_{141}	12k		½w	L_8 to L_{10}	Green Indicator	
R_{142}	56k		2w	L_{11} to L_{13}	Red Indicator	
	RELAYS				FUSES	
K_1	3PST	240V	90A	F_1	20 amp. Buss super lag	
K_2, K_3	3PDT	10k ohm	6.1 ma	F_2	20 amp. Buss super lag	
K_4, K_5	2PST	110V	10A	F_3	20 amp. Buss super lag	
K_6, K_7	2PDT	110V	10A	F_4	5 amp. 250 V	
K_8, K_9	1PST and	3,500V	1A	F_5	1 amp. 250 V	
	1PDT	110V	1A Special Relay	F_6	1 amp. 250 V	
K_{10}	1PST and	6,000V	10A	F_7	1 amp. 250 V	
	1PDT	110V	1A			
			Special Relay		POWER SUPPLIES	
K_{11}	4PDT	110V	10A Latching Relay	PS_1	+100 VDC	rated 100 ma. 0.1% regulation
K_{12}	1PST-NC	110V	2 sec. time Delay Relay	PS_2	+300 VDC	rated 100 ma.

TABLE I. (Continued)

K_{13}	1PST-NC	110V	180 sec. time Delay Relay
K_{14}, K_{15}	4PDT	110V	10A Latching Relay
K_{16}, K_{17}	1PST-NC	110V	180 sec. time Delay Relay
K_{18}	2PDT	110V	10A
K_{19}, K_{20}	2PDT	10k ohm	4.5 ma

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