High-power microwave pulse generator

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An inexpensive alternative to commercial high-power microwave pulse generators is described. The present high-power microwave pulse generator utilizes a surplus MIT model 3 Mark II hard tube modulator and 2J51 magnetron. The basic design and technical details of the pulse generator are presented. The pulse generator is designed to produce 8.5–9.6 GHz pulses with pulse lengths ranging from 2 to 4 μs, with a nominal power output of 20 kW and a maximum duty cycle of 0.001.

I. INTRODUCTION

High-power microwave pulse generators are important for research in nonlinear high-frequency magnetics and other areas of microwave technology. While such pulse generators are available commercially, the cost is often too high for modest research budgets. The pulse generator described here is easily fabricated from standard inexpensive components and hard tube modulator/magnetron units available on the surplus market at modest cost.

The high-power microwave pulse generator described here was developed at Colorado State University for use in the high-power microwave characterization of ferrite materials for radar applications. The generator utilizes an MIT model 3 Mark II hard tube modulator and a Raytheon 2J51 magnetron tube. This paper is primarily concerned with the workings of the pulse generator and its subsystems. The first section of this report presents a general overview of the overall pulse generator system. The second section provides a detailed description of the hard tube modulator (HTM) unit, the system interconnects, and the magnetron. The third section gives a description of the pulse generator/sync (PGS) unit which provides high-voltage drive pulses for the pulse generator system.

II. OVERALL SYSTEM

A block diagram of the pulse generator system is shown in Fig. 1. The key element in the system is an MIT model 3 Mark II hard tube modulator unit developed at the MIT Radiation Laboratory in the 1940's for airborne radar applications.[1] The pulse generator system is designed around this unit. This unit is labeled HTM in Fig. 1. This HTM unit has been extensively modified for laboratory use. The unit was (1) mounted inside a rack mount console, (2) fitted with front panel switches, fuses, power controlled variacs, and internal connectors, (3) powered by an 800 Hz power supply and a 24 V dc power supply (in addition to 60 Hz, 110 V ac power), and (4) fitted with a frequency tunable 2J51 magnetron.[1] The magnetron, labeled MAG in Fig. 1, feeds a reversed high-power isolator used as an attenuator. Power can be routed to a spectrometer, labeled OUTPUT in Fig. 1, or to a DUMMY LOAD. The present system feeds an X-band high-power spin-wave linewidth spectrometer similar to the system developed by Patton and Green.[2] The focus of this paper is the microwave pulse generator system, not the spectrometer.

Sync pulses to trigger the entire system and drive the HTM unit are generated in the pulse generator sync unit, labeled PGS in Fig. 1. The PGS unit serves two functions. The first is to provide a sync pulse at a selected subharmonic of the 800 Hz power supply frequency. This pulse serves as a sync signal for the entire system. Such synchronization eliminates signal "jitter" due to pick-up from the 800 Hz power supply. Under normal operation, the repetition rate is set to the fourth subharmonic of the 800 Hz power supply frequency, or 200 Hz. This repetition rate yields a duty cycle slightly below 0.001 for the maximum pulse width of 4 μs. The second function of the PGS unit is to provide a 90 V, 4 μs pulse output to drive the input stage of the hard tube modulator HTM unit.

Figure 1 also shows a data acquisition/control unit, labeled DAC, connected to the PGS unit. The specific DAC unit for our system works in conjunction with the spin-wave spectrometer mentioned above, which will not be discussed here. This particular DAC unit functions as follows: (1) The DAC is triggered off the pulse generator driver pulse. (2) It, in turn, provides the various driver signals for the microwave switches in the spin-wave spectrometer detectors, power monitor, etc. (3) The DAC then provides analog output signals to generate x-y recorder plots of absorbed power versus microwave field amplitude for the measurement of high-power processes in various magnetic materials. The DAC unit and the companion spectrometer operating principles follow the basic description of Patton and Green.[2] It should be noted that the DAC/spin-wave spectrometer described above represents one particular application of the high-power microwave pulse generator which is the focus of this paper. Other applications will require other types of microwave appendages and DAC configurations.

III. THE HARD TUBE MODULATOR UNIT AND MAGNETRON

The basic function of the hard tube modulator HTM unit is to provide 10 kV–10 A level pulse power to an internally mounted magnetron, labeled MAG in Fig. 1, for the generation of high-power pulse microwave power. A functional diagram of the HTM unit is shown in Fig. 2. The essential purpose of this unit is to take a voltage driv-

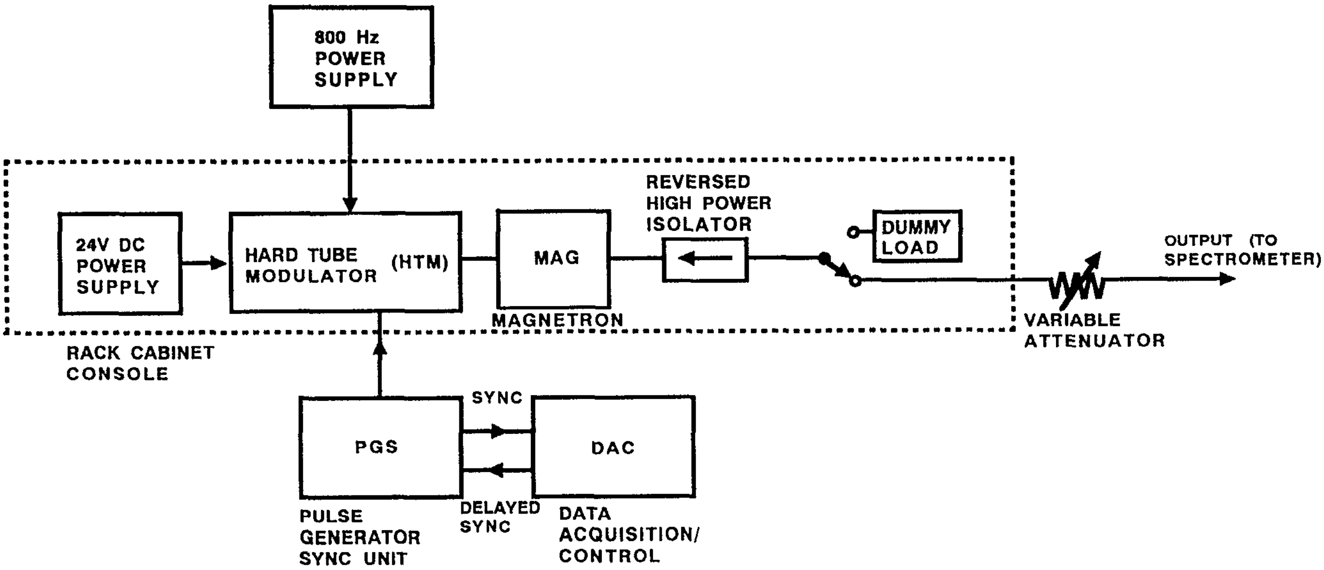

FIG. 1. Block diagram of the pulse generator system.

ing pulse, shown on the left of Fig. 2 as the 100 V PULSE INPUT, and generate a fast rise time 2–4 μs wide pulse at 10–15 kV to energize the magnetron, shown on the right of Fig. 2 as OUTPUT. The hard tube modulator HTM unit consists of everything in Fig. 2 to the left of the magnetron. The basic operation is as follows: (1) The high-voltage power supply charges the capacitor C to voltage V_{cc} through resistors R_1 and R_2. (2) The pulse input is amplified by the driver amplifier D and then applied to switch tube S. (3) With the switch tube in its "on" or conducting state, R_1 is shorted and the capacitor C discharges through the magnetron, by passing R_2. (4) When the switch tube returns to its "off" state, the capacitor C is recharged to V_{cc} through R_1 and R_2 by the high-voltage power supply P. As indicated above, the HTM unit is used to drive a Raytheon 2J51 magnetron. The 2J51 thereby produces microwave pulses at a nominal frequency of 9 GHz, a nominal power of 20 kW, and nominal pulse widths of 2, 3, or 4 μs. The pulse width is controlled by a switchable lumped constant delay line circuit in the HTM unit. Pulse widths of 4 μs are usually used.

MIT model 3 Mark II hard tube modulator modules can be obtained inexpensively, albeit with some difficulty, from various surplus electronics houses. The unit is well documented.[1] The documentation includes wiring diagrams and oscillograph patterns for typical waveforms. The documentation also contains considerable detail on circuit design considerations for the unit. This documentation should be considered mandatory reading prior to any design, construction, and/or subsequent laboratory use of a pulse generator system based on this report.

The MIT unit was produced and is nominally available in two versions, designated Mark I and Mark II. The Mark I unit requires 110 V ac input power at 400–2000 Hz. The Mark II unit requires ac power over the more restricted power range 800–1600 Hz. Both versions require 24 V dc to operate relays and blowers. Both versions were designed to supply 12 kV, 12 A magnetron drive pulses of 0.5, 1, and 2 μs duration with a maximum duty cycle of 0.001. The units require 100 V, 1 A input drive pulses of 4 μs or so duration. These pulses drive a lumped constant delay line pulse forming network, and the exact shape and pulse length is not critical. As described above, the units function by discharging a capacitor through the magnetron by means of a switch tube. The storage/discharge capacitor in the Mark II version is 0.15 μF, three times the capacitance

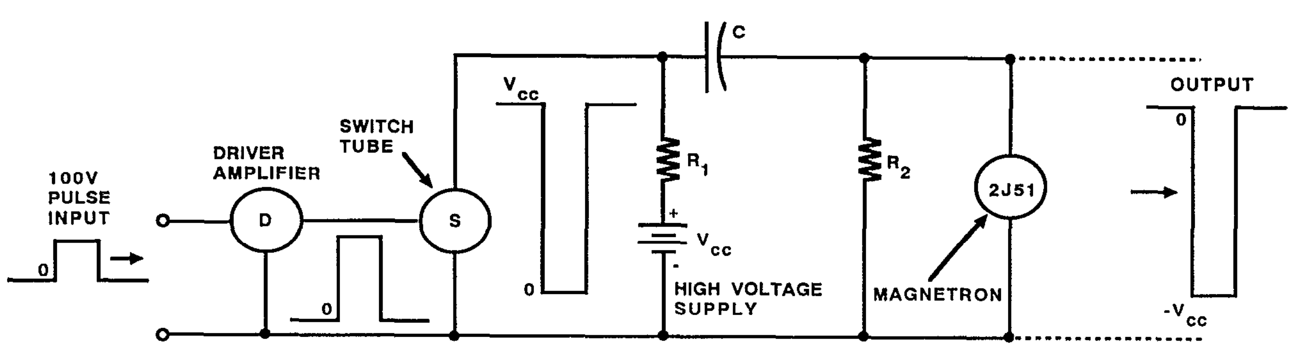

FIG. 2. Functional layout of the hard tube modulator.

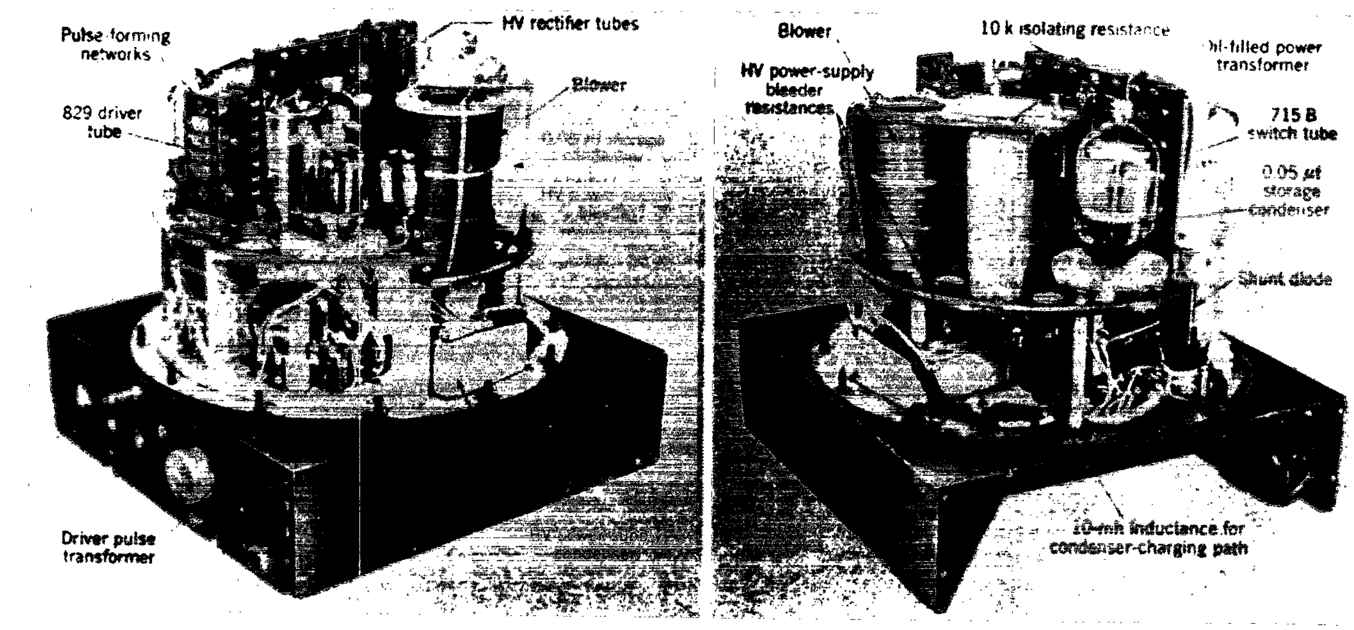

FIG. 3. Photographs of the MIT model 3 Mark II hard tube modulator unit.

of the Mark I unit. This means that for the Mark II unit, the droop in the high-voltage pulse during discharge is 1/3 that for the Mark I unit. This is an important consideration for microwave ferrite work because of the need to extend the magnetron pulse width. For this reason, the Mark II unit was chosen for this system.

Figure 3 shows two photographs of the basic MIT model 3 Mark II HTM unit which have been reproduced

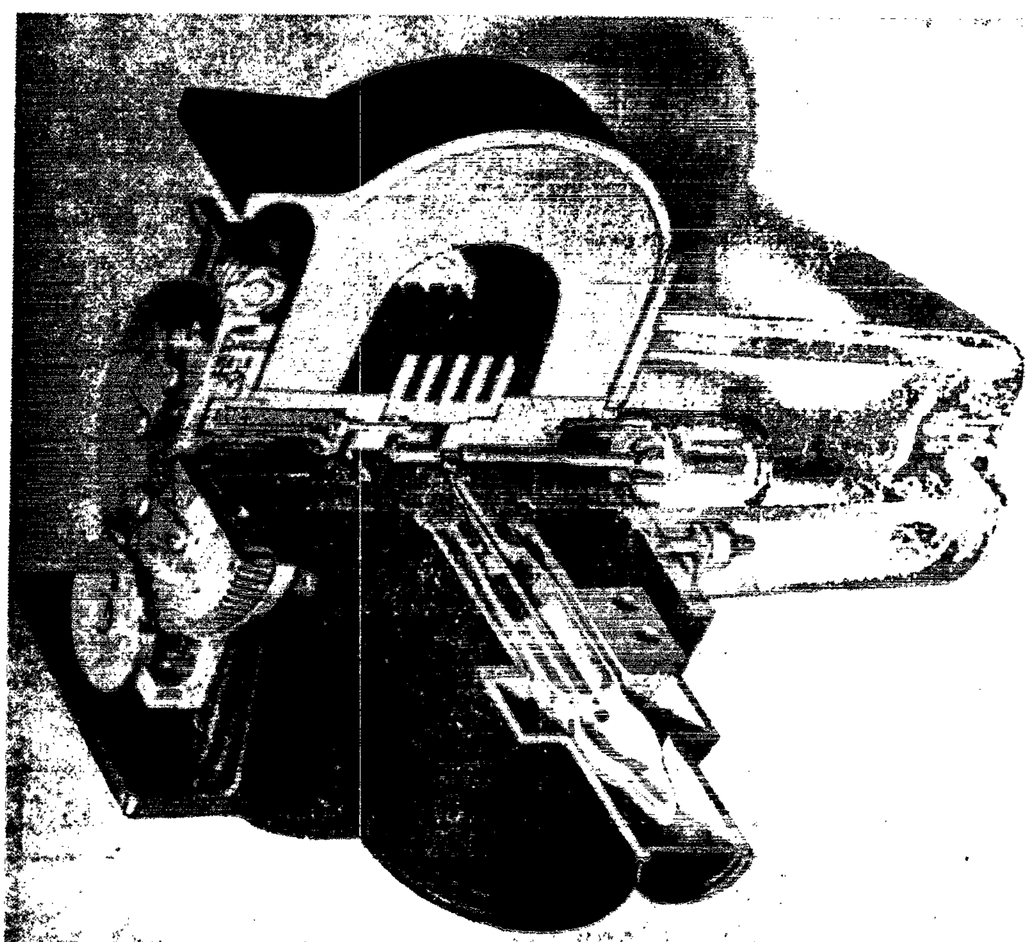

FIG. 4. Cut-away view of the Raytheon 2J51 magnetron.

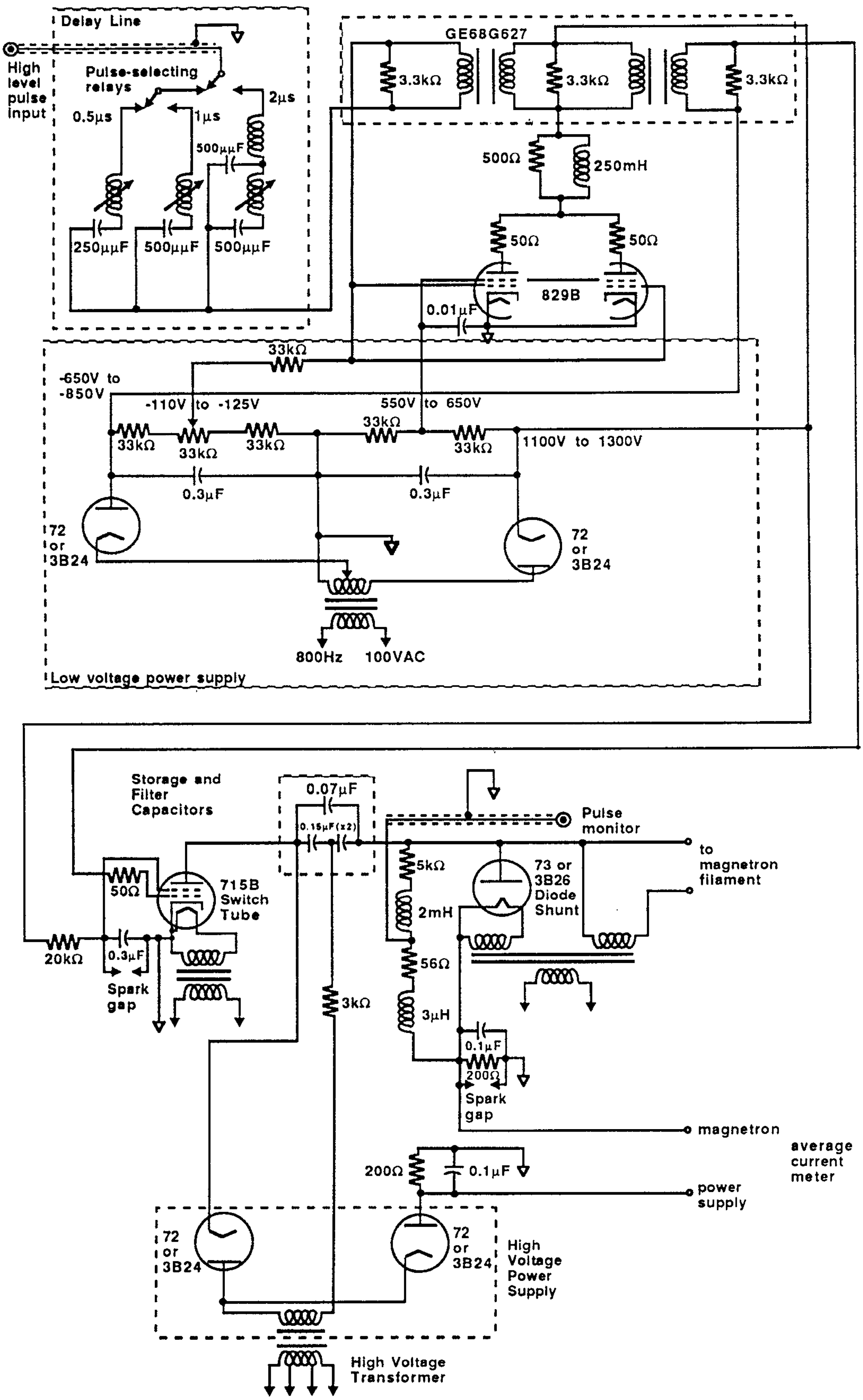

FIG. 5. Overall functional schematic of the hard tube modulator.

from Glasoe.[1] The photographs are not particularly crisp, but the basic components can be seen with reasonable clarity. Figure 4 shows a cut-away view of the 2J51 magnetron, reproduced from Smith.[3] As shown in Fig. 4, the high-voltage filament/cathode is mounted axially through one end of the magnetron biasing magnet assembly. The filament/cathode connections are through the two terminal high-voltage glass insulators in the top of Fig. 4. The mag-

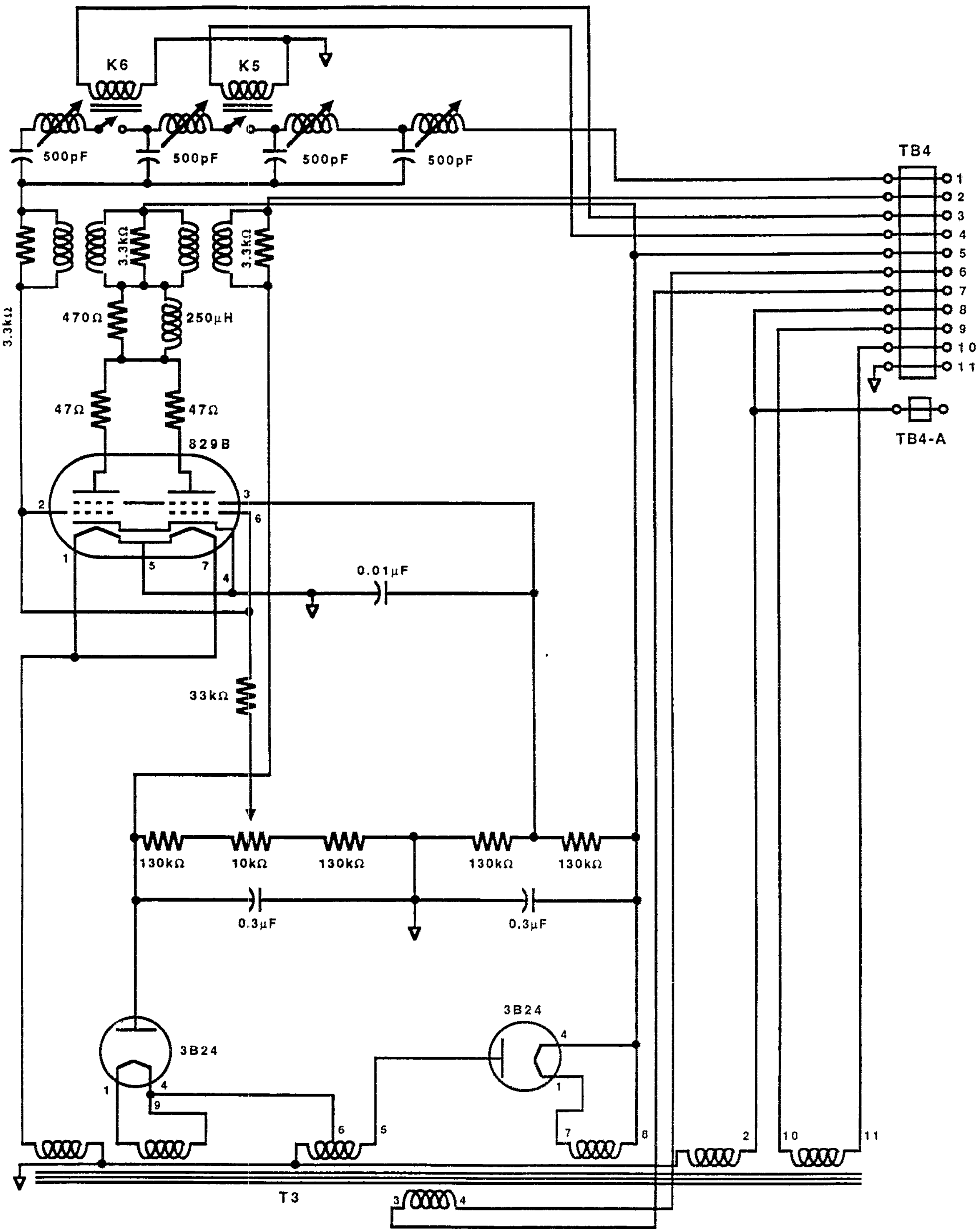

FIG. 6. Wiring diagram of the low-voltage power supply and the driver amplifier stage.

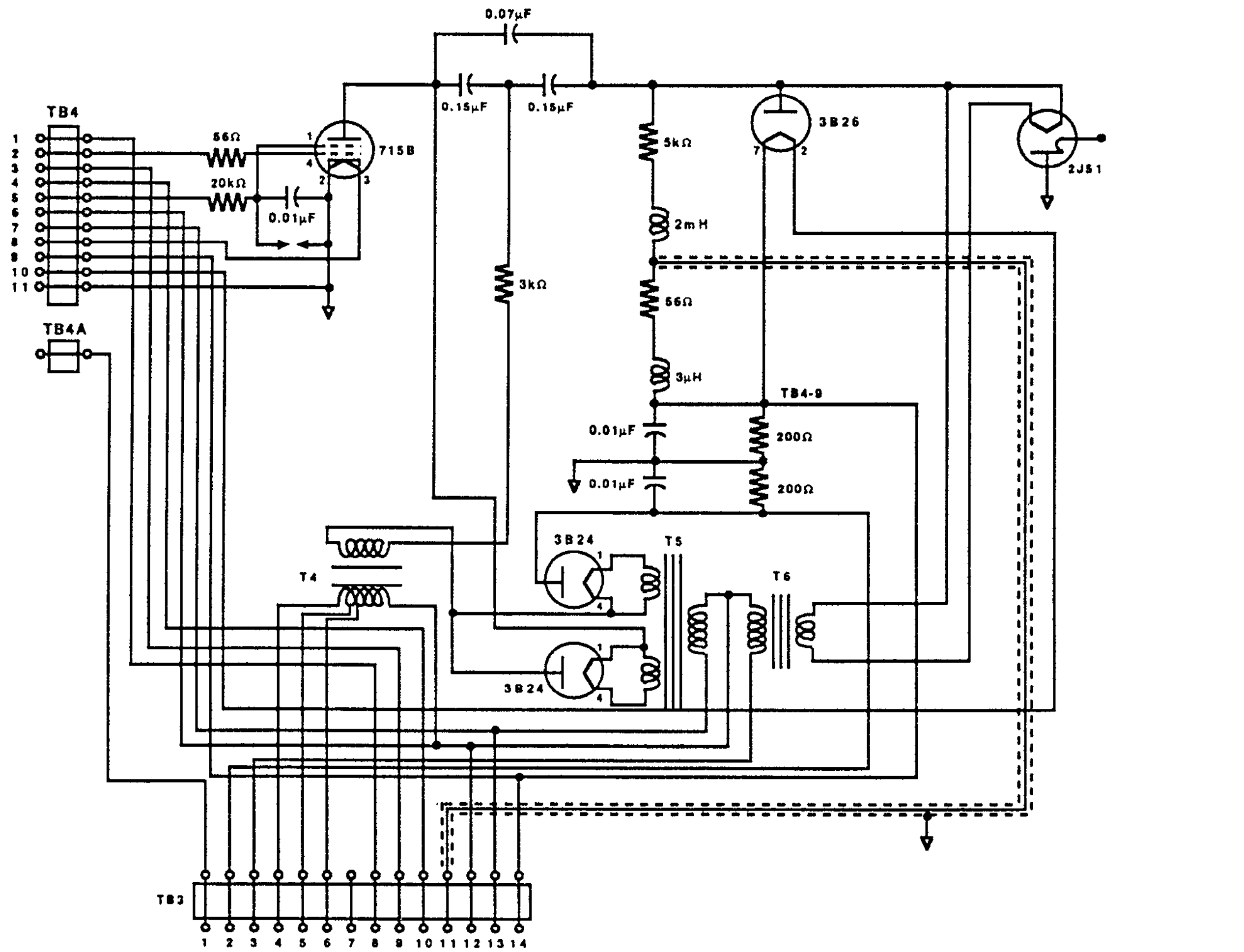

FIG. 7. Schematic wiring diagram of the switch tube section, the high-voltage power supply section, and the capacitor/magnetron circuitry.

netron cavity is located in the middle of the magnet assembly. The mechanical tuning mechanism is mounted on the bottom of the magnet assembly, as shown. Tuning is accomplished by means of 12 copper pins which may be inserted to a variable depth in the 12 holes of the anode block. The pins are attached to a plunger which is actuated by an external mechanism through a metal bellows. The external drive consists of a round gear on the end of a tube and a worm gear. Both gears are evident in Fig. 4. The output waveguide is evident in the left part of the figure, facing backward.

Figure 5 shows an overall functional circuit schematic diagram of the HTM unit, as adapted from the wiring diagram given by Glasoe.[1] This figure offers an overview of the specific operational circuit components which make up the hard tube modulator and shows the relationship between these components in the overall HTM operational system. Specific component values and voltage limitations are also shown in Fig. 5. The basic HTM system components are as follows: (1) switch selectable input delay line, (2) low-voltage power supply (for driver and switch tube), (3) blocking oscillator/amplifier (829B tube), (4) inverting pulse transformer (GE68G627), (5) switch tube (715B tube), (6) storage, filter, and pulse discharge capacitors, (7) high-voltage power supply, (8) diode shunt (3B26), and (9) magnetron connections. A discussion of these subsystems is given below.

It is important to note that the HTM system contains high voltages (components floating at approximately ~ 10 kV). Extreme care should be taken when working with the internal elements of the HTM unit.

The switch selectable delay line pulse forming network section of HTM is shown in the upper left portion of Fig. 5. These switches control the active delay line characteristics and the output pulse width. The pulse input which drives the delay line must be in the 100 V range, but the pulse shape is not critical. In the current system, a 90 V, 4 μs pulse is used. As shown in Fig. 5, the delay line in the Mark II unit was originally set up for 0.5, 1, and 2 μs pulse outputs. For the pulse generator system, these pulse widths were modified to 2, 3, and 4 μs by replacing the 0.5 μs delay line section in Fig. 5 with the 1 μs delay line from another unit and changing the switch and relay connections. Concentrations on these pulse forming networks are discussed in detail by Glasoe.[1]

The delay line feeds the driver amplifier stage, which consists of an 829B dual tetrode vacuum tube operated as a blocking oscillator. Power for this driver stage and the 715B switch tube comes from the low-voltage power supply just below the delay line section of Fig. 5. This power

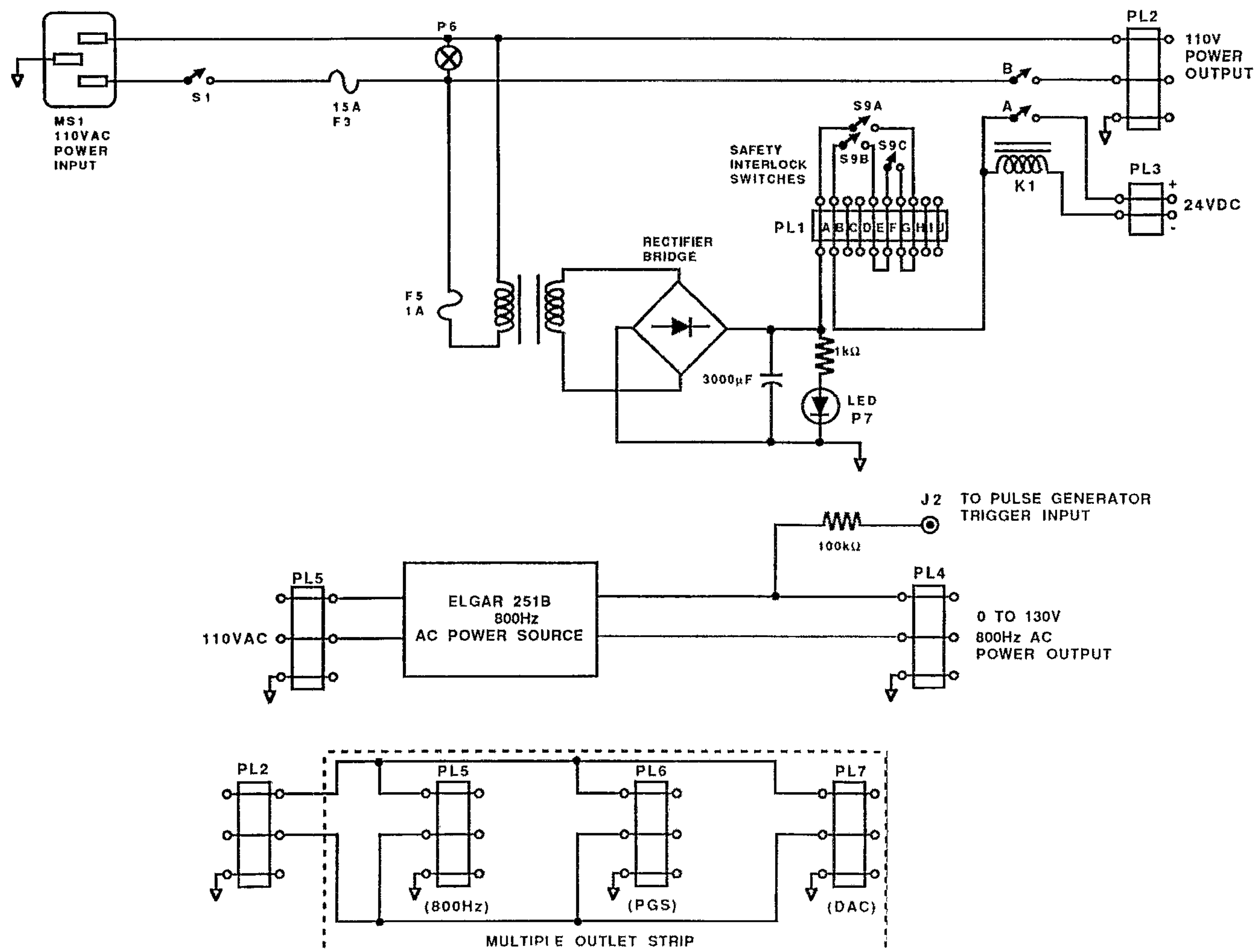

FIG. 8. Main power section.

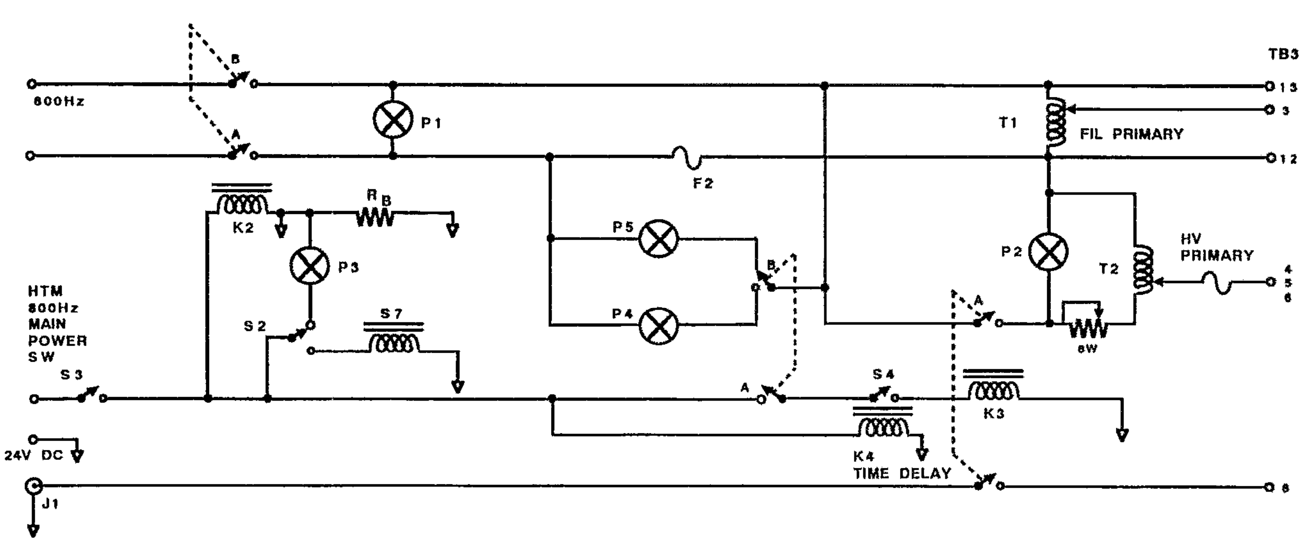

FIG. 9. Overview circuitry for the 800 Hz power distribution and the relay interlock circuitry.

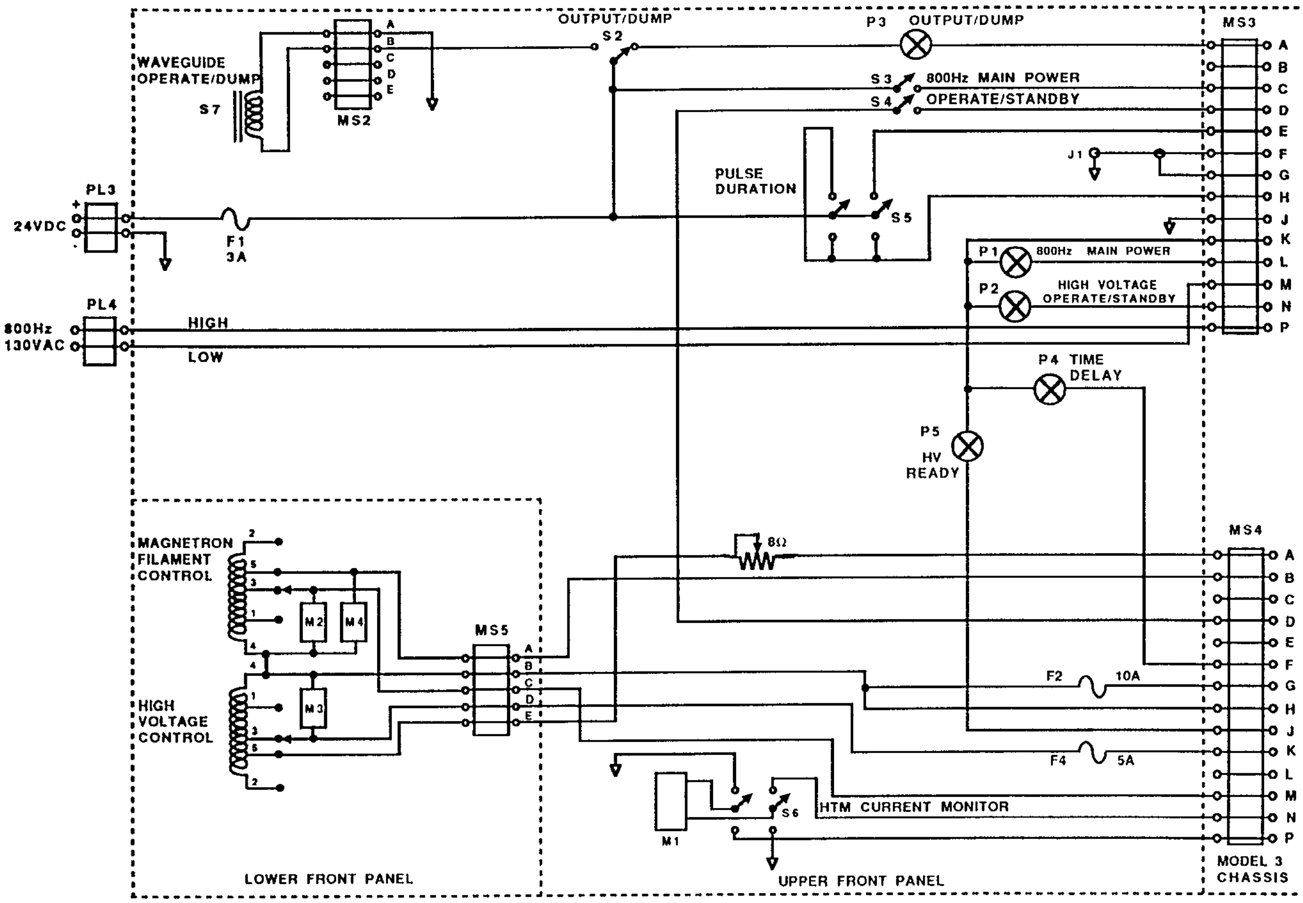

FIG. 10. Variac, meter, switch control, and status lamp circuitry.

supply utilizes two 3B24 rectifier tubes in separate half-wave rectifier configurations to provide the 550–650 V dc positive plate voltage for the 829B driver stage and 110–125 V dc negative cutoff voltage for the switch tube grid. The output of the 829B blocking oscillator is inverted by the GE pulse transformer in the plate circuit and applied to the negatively biased 715B switch tube grid.

The 715B switch tube stage, shown in the lower left portion of Fig. 5, is a critical element of the HTM system. The requirements on this tube are substantial. It must be able to withstand voltages in the 10–15 kV range, and have sufficient cathode emission for the required 10–15 A magnetron current. Glasoe[1] discusses the applicability of and limitations on the 715B tetrode to this task. The 715B tube is maintained in an "off" state by the negative 550–650 V dc bias from the low-voltage power supply. The positive voltage from the GE pulse transformer drives the 715B into an "on" state for the duration of the pulse, and the tube discharges the storage and filter capacitor through the magnetron.

The high voltage power supply for the HTM unit is shown in the lower portion of Fig. 5. This supply uses two 3B24 rectifier tubes operated in a voltage doubler configuration. The basic function of this supply is to charge the 0.15/0.15/0.07 μF storage-filter capacitor network shown just to the right of the switch tube in Fig. 5. The capacitor network serves the dual function of filter and storage. The various resistors and inductors in the circuit serve to isolate the high-voltage power supply during the capacitor discharge through the magnetron filament/cathode assembly to ground. Figure 5 shows a 3B26 diode across the 2 mH inductor in the charging circuit. This diode shunt serves to short circuit the inductive overshoot at the end of the high-voltage pulse due to the 2 mH inductor.

Figure 5 shows a common filament transformer for the diode shunt and the magnetron. The hookup is shown in this way for schematic purposes only. In the actual unit, the diode shunt filament is powered from the low-voltage supply transformer in the center of Fig. 5 and the magnetron filament derives from the transformer shown. As part of the modification of the system for laboratory use, this separate magnetron filament transformer is powered up for start-up operation and then powered down during operation. It is found that powering down the magnetron filament during operation yields cleaner microwave pulses. These points will be discussed in more detail below.

The average magnetron current is monitored by inserting a current meter in the storage capacitor charging circuit. This meter is connected to the average current meter terminals on the right side of Fig. 5. The average magnetron current is taken to be the same as the average charging

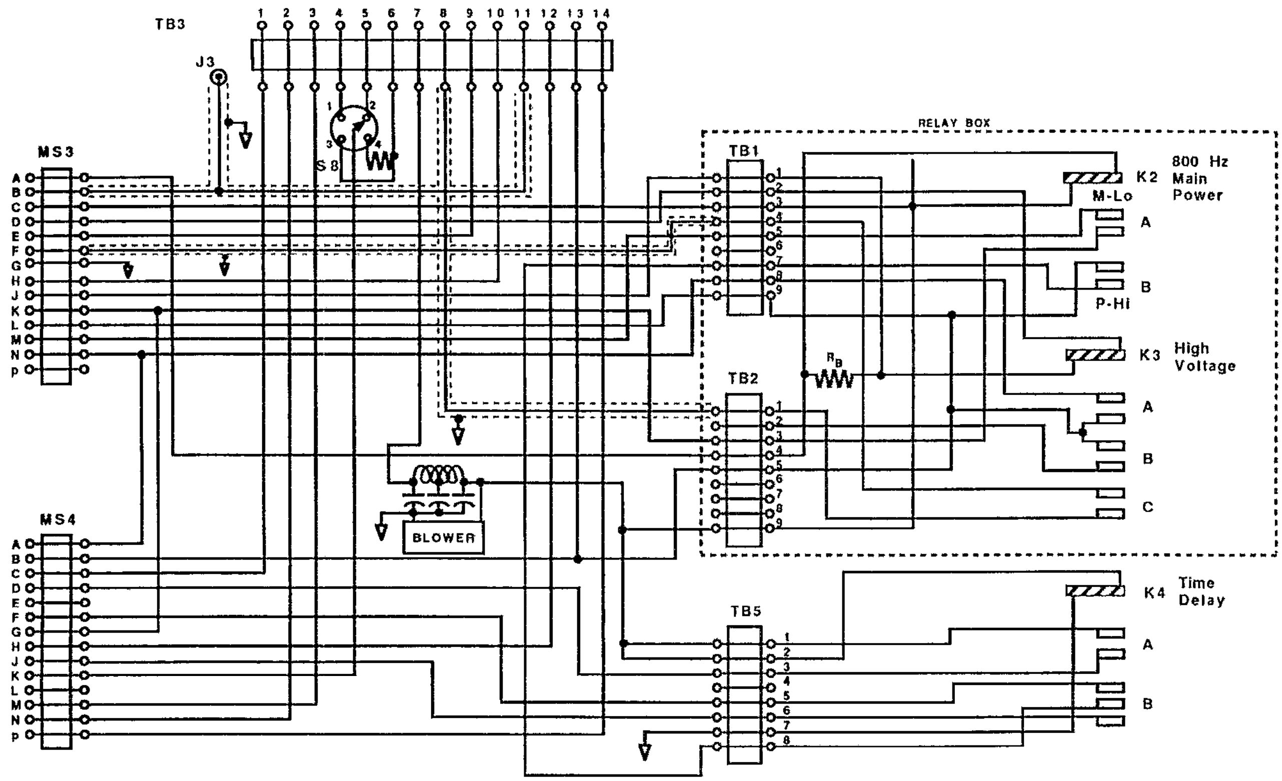

FIG. 11. Relay and interlock circuitry.

current for the storage capacitor network. The shielded cable provides a monitor for the pulse output.

As stated previously, the purpose of the switch tube is to discharge the 0.15/0.15/0.07 μF capacitor network which is initially charged to the high-voltage power supply voltage. This discharge takes place through the magnetron and generates the desired high-power microwave pulse. The positive current path during discharge is from the positive side of the capacitor, connected through ground through the "on" state of the switch tube, through the grounded magnetron anode block (plate) to the magnetron filament/cathode, and back to the initially negatively charged side of the capacitor. The 12–15 kV discharge through this path yields a 12–15 A discharge current which produces the desired magnetron microwave output pulse.

The Magnetron connections, but not the actual 2J51 magnetron, are shown in Fig. 5. The 2J51 magnetron is tunable over the range of 8.5–9.6 GHz by means of copper shunts which are moved in or out of the cavities in the grounded anode block (Collins[3]). The 2J51 also has removable magnetic shunts which permit operation at somewhat lower pulse voltages and currents down to 10 kV and 10 A. The 2J51 is capable of nearly 65 kW of output peak power. As employed in the pulse generator system, the output is about 20 kW.

Figures 6 and 7 show detailed circuit diagrams for the HTM subsystems seen in Fig. 5 and discussed above. Figure 6 shows the actual wiring diagram of the low-voltage power supply and the driver amplifier stage. Figure 7 shows a schematic wiring diagram of the switch tube section, the high-voltage power supply section and the capacitor/magnetron circuitry section of the HTM unit.

Figures 8–11 show various subsystems for the overall system. Figure 8 shows the main power supply components and system connections. Primary 110 VAC 60 Hz power enters through connector MS1 in the upper left portion of Fig. 8. The circuitry provides switched 110 VAC 60 Hz power, 24 VDC power and 0–130 VAC 800 Hz power to various points in the system. Safety interlocks are provided for the 24 VDC and 800 Hz power outputs.

Figure 9 shows a functional diagram for the interlock circuitry for the proper sequential application of 800 Hz power to the HTM system components. Activation of the main power switch S3 applies 800 Hz power to the magnetron filament through variac T1 and energizes the time delay relay K4. The closing of relay K4 provides 800 Hz power to variac T2 for the high-voltage power supply in the HTM unit. It also connects the high-voltage input to the HTM driver stage through J1.

Figure 10 shows the variac, meter, switch control, and status lamp circuitry, and the interconnects to the HTM system (See also Fig. 11). Figure 11 shows a detailed diagram of the relay circuitry (Fig. 9) and further interconnects to the HTM unit. Note that the main connector to the HTM unit, TB3, is the same connector shown in Fig. 7.

IV. THE PULSE GENERATOR/SYNC PGS UNIT

The input drive pulses for the HTM unit are provided by the pulse generator/sync PGS unit. These pulses consist

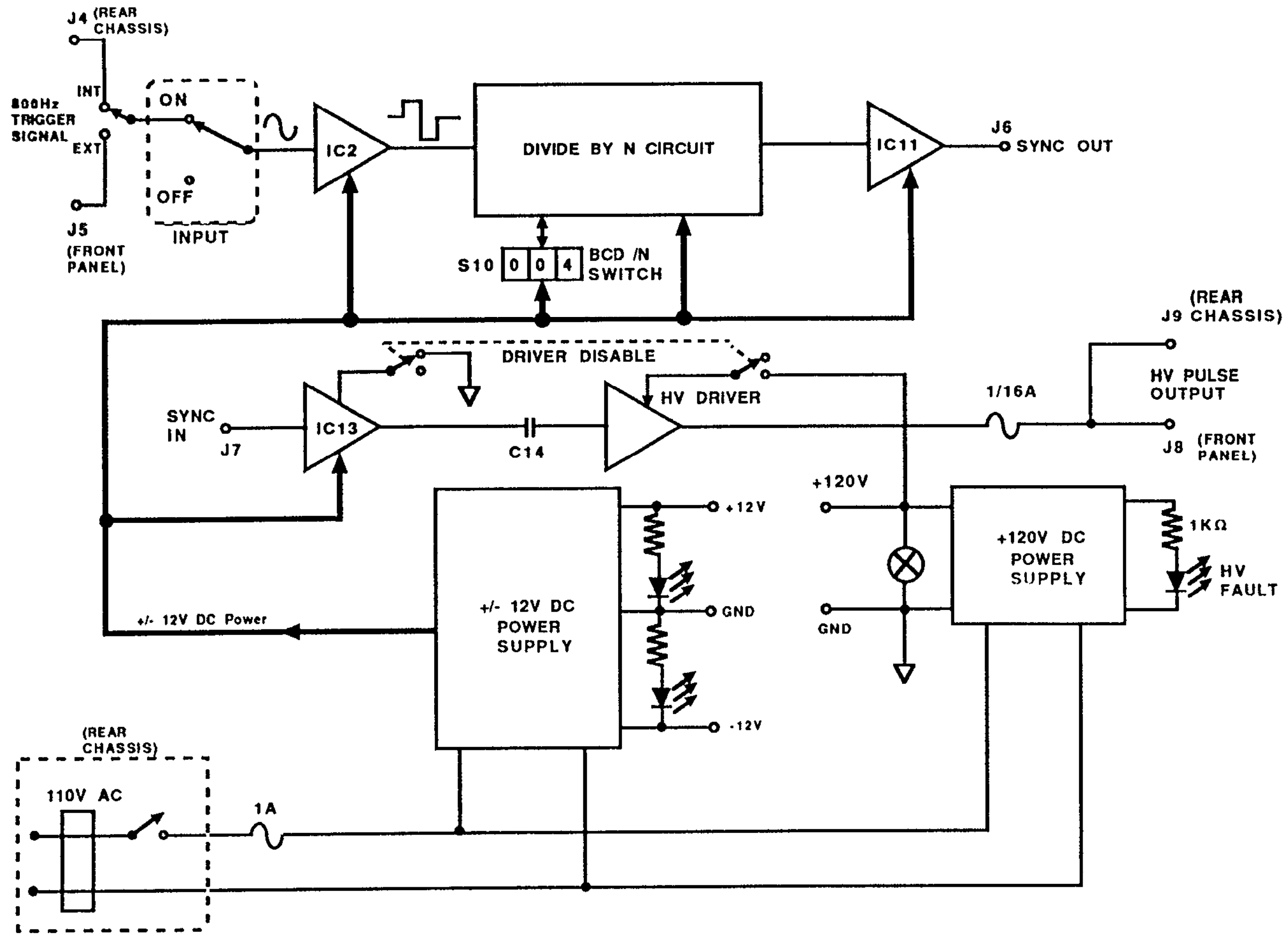

FIG. 12. Pulse generator/sync unit block diagram.

of 100 V–4 μs pulses which are synced to a subharmonic of the 800 Hz power supply signal, usually the fourth subharmonic at 200 Hz. The 100 V–4 μs pulse is adequate to drive the input delay line and driver amplifier circuitry of the HTM unit. The subharmonic synchronization helps to eliminate ac noise when observing low-level spectrometer output signals which derive in one way or another from the microwave pulse output signal from the pulse generator system.

A block diagram of the PGS unit is shown in Fig. 12. The central elements in the PGS unit are the divide by N circuit block shown in the top part of the figure and the high-voltage driver stage just below the divide by N section. The bipolar ± 12 V dc and the $+120$ V dc power supplies for these units are shown at the bottom of the figure. The ± 12 V dc supply powers the divide by N circuit and the low-level stage of the high-level pulse driver circuit. The basic functions of the PGS unit are as follows: (1) The unit takes a low-level 800 Hz signal input, typically 5 V rms, and uses this signal to generate an 800 Hz square wave following IC2. (2) A "divide by N" circuit is then used to generate a square wave at some 800 Hz subharmonic, e.g., $800/N$. (3) This $800/N$ subharmonic square wave is used to provide a sync out signal for the other elements of the microwave pulse instrumentation with the pulse generator system. Under normal operation, this sync out signal is routed through a suitable time delay and then applied to the sync in input for the PGS unit, shown in Fig. 12. (4) The sync in signal is applied to a pulse forming circuit and high-voltage (120 V dc) driver amplifier to obtain a nominal 100 V, 4 μs driver pulse for the HTM unit.

The divide by N function is needed for two reasons. The first reason, discussed briefly in the previous sections, is simply to provide duty cycle control for the high-power microwave pulse output. The system is normally operated in a "divide by 4" mode, with the high-power pulse repetition rate at 200 Hz. For a 4 μs pulse output, this yields a duty cycle of 0.0008. The HTM is designed to operate at a nominal duty cycle of 0.001. The second reason, also discussed above, is to allow the pulses generated in the spin-wave spectrometer (or other receptor instrumentation) to be synced to the 800 Hz power. This is necessary because of the low-level microwave pulse output signals which must often be analyzed in the course of a given measurement procedure. The "jitter" on the output due to the 800 Hz supply can be quite bothersome and render accurate measurements extremely difficult. One solution is simply to sync the pulse repetition rate to some subharmonic of the

800 Hz ac power. The divide by N sync circuitry allows both objectives to be accomplished.

V. DISCUSSION

An inexpensive, easily fabricated high-power microwave pulse generator has been described. The pulse generator utilizes an MIT model 3 Mark II hard tube modulator and a Raytheon 2J51 magnetron tube, both of which can be located on the surplus electronics market. Circuit diagrams and fundamental electronic analyses for the pulse generator and its subsystems are provided. The pulse generator has been used for research in high-power microwave magnetics.

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