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A New 200 kW, 800 MHz Transmitter System for Lower Hybrid Heating

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ABSTRACT

This paper describes a new rf heating system which has just been completed and is being installed on the ATC machine. It will be used for Lower Hybrid heating experiments and, as such, will be the first high power rf equipment to be constructed for this purpose.

The system utilizes four UHF TV klystrons to generate at least 200 kW of power at a frequency of 800 MHz. Pulse widths can be varied from 20 μsec. up to 20 msec. A radar type floating deck modulator along with photo-optical transmitting and receiving devices have been incorporated into the system to provide the pulse fidelity and versatility which characterizes this equipment.

Modular construction was emphasized in the design, when possible, to reduce maintenance and down time in the advent of component failure.

Hybrid combining techniques are utilized in order to provide two 100 kW feeds into the machine.

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INTRODUCTION

In the fall of 1973, work was begun on a new RF heating system to be used for lower hybrid experiments on the ATC machine. Physics requirements dictated that the frequency of this system lie in the UHF range. Study of available high power rf sources, machine and plasma parameters led to the selection of 800 MHz as the optimum frequency.

Other technical requirements included were:

RF power out	200kW
Pulse width	20 μsec - 20 msec
Pulse repetition frequency	1p/20 sec
Power droop during pulse	12%

Several interesting design techniques and philosophies are utilized in this system which uses commercial TV klystrons operating as a radar transmitter for plasma heating. The entire system was designed and constructed at PPPL.

RF System

A block diagram of the rf system is shown in Figure 1.0. It shows a single source which is a crystal controlled, solid state exciter capable of a 10W output. This signal is divided four ways by a hybrid power splitter and fed to each of four HPA (high power amplifier) cabinets. Phase shifters and attenuators for amplitude adjustment are incorporated in each of the four output legs to provide the adjustments necessary for high power combining in the output stages of this system.

The first experiments will transmit the rf into two ports of the ATC machine. Figure 1 shows two sets of two HPA's combining to form the two 100 kW feeds for the ATC machine.

Each signal fed to an HPA cabinet is amplified by a solid state 10 W amplifier to make up for the 6 to 10 dB of power loss caused by the long transmission run from the exciter (Driver/Control Cabinet) to the HPA stage.

The heart of the rf system is a VA-955 klystron amplifier. This tube is a highly reliable, 5 cavity, electromagnetically focused klystron. The tube is used in commercial UHF TV transmitters and is rated at approximately 55 kW of rf output. It also features a modulating anode which makes it relatively easy to switch the beam current on and off.

The modulating anode is similar to the grid of a standard vacuum tube. The intercept current is very low (on the order of a few milliamps), however, unlike the control grid of a tube, the mod anode must be pulsed the full beam voltage in order to allow the tube to go full conduction, i.e. $\mu = 1$.

Modulator

A floating deck modulator was designed to switch the modulating anode of the klystron and turn the tube on and off. The mode of operation would be to gate the beam on and inject the rf drive pulse within the video pulse. The modulator had to have a moderately fast rise time ($\simeq 2$ μsec) and have pulse width capability of 20 μsec to 20 msec.

Two major requirements for the modulator are to (1) pass enough current through it to discharge the load stray capacity rapidly and (2) maintain or pass the current from the klystron mod anode during the pulse. (See Figure 2.)

The circuit works in the following manner. V_1 is the "ON" switch, and must pass sufficient current during the rise time of the pulse to rapidly turn on the klystron. This rise time is determined by the approximate relationship:

$$\Delta T \cong \frac{\Delta E C_s}{I}$$

Where ΔE = voltage change (25 kV)

C_s = stray or shunt capacity to ground (200 pf)

I = current through V_1 (2.5A)

ΔT = rise time desired

C_s was kept to less than 200 pf which allowed the modulator to achieve rise times on the order of 2 μsec with about 2.5A of current.

The modulator tube selected is a 4PR250C tetrode rated at 50 kV and 3 to 4A of plate current depending on drive and screen voltage. When the mod anode is pulsed to 25 kV, full beam current from the klystron will flow. The mod anode intercept current during this time will be only 2 mA. This current added to that flowing through the mod anode resistor is the total current that must pass through the ON switch tube.

Most of this current comes through R_m. If ones makes R_m too high in value then the leakage current through the switch tube V_1 causes R_m and V_1 to become a voltage divider which will pull the mod anode away from klystron cathode potential during the "OFF" period thus turning the klystron on. Since the current through V_1 need be only 10's of milliamps, the screen voltage of this "ON" tube can be low ($\simeq$ 100V). This enables one to operate the tetrode switch tube in an interesting mode. Figure 3 depecits the plate voltage (E_p), plate current (I_p), screen voltage (E_{c2}) and screen current (I_{c2}) during a typical pulse. As shown, low tube drop (150V) can be tolerated because of the low plate current requirement and because of this we can let the screen voltage "bottom out" with the plate. Its a very effective technique and doesn't require a large screen supply.

Two modulators operate with each klystron. One turns the tube on and the second functions as a "tail biter" (see Figure 2). When V_1 turns off, the mod anode potential must return to the cathode potential in order to cut the klystron beam off. For this to happen, the stray capacity C_s from the mod anode to ground must be recharged and without a tail biter, the current recharging C_s will be limited by the high resistance R_m. This time constant is much too long as shown in Figure 3A.

The function of the Tailbiter is to shunt R_m with a low impedance path (V_2) for the fall time of the pulse allowing C_s to recharge quickly. The effect is shown in Figure 3A.

Mechanical Features

The modulator and its power pack (contains all auxilliary supplies) are shown in Figure 4. Its constructed in modular form to facilitate easy removal and replacement in the modulator tank. It features a solid state grid driver and light emitting and receiving diodes in an opto-coupling scheme which transmits the wide bandwidth information from ground to the deck floating at 25 kV.

The klystron modulator assembly is mounted in an oil filled tank. While oil is not necessary at these voltage levels, it enabled us to reduce the size of the system and also provided excellent cooling of all the electronic components. This tank also serves the dual function of a movable mounting platform for the klystron and its focus coil.

The modulator/klystron tank assembly rolls into the HPA cabinet and is shown along with the Driver/Control cabinet in Figure 5.

Fault Detection and Protection

Fault detection in this system is divided into two basic categories:

I. Slow

II. Fast

A. RF

B. Klystron beam

Slow protection is accomplished in the traditional fashion by using relay logic.

The system is self protective and immune to operator error. Self diagnostics are designed to indicate to the operator trouble areas in the system.

Fast protection is accomplished by a new Four Channel Fault Detector specifically designed for this project. The circuit is shown in Figure 6. The interesting part of this fault detector is the lock out feature. It's a four channel system which will lock out the other 3 channels the instant a fault is sensed in one of the channels. This philosophy was followed to circumvent the age old problem of having every light on a fault detection system go on the instant a major fault was experienced any place in the system.

RF protection is accomplished by monitoring the VSWR (actually reflected power) and also by an arc detector circuit The arc detector circuit is rather unique in that it not only senses arcs in the output transmission line of the klystron but it also monitors its own circuit to see that it is functioning. This is accomplished by having a test light on at a very low level all the time. The circuits sense this level and relay to the control system that the arc detector actually is functioning. If an arc in the output transmission line were to occur, the light instantly would increase by at least an order of magnitude thereby changing the state of the arc detecting circuit which would cause the removal of rf drive.

Klystron arcing protection is accomplished by sensing high beam and body currents and relaying this information to the fault detector.

Transmission System

The transmission system is composed of 3-1/8 inch 50 ohm rigid coaxial line and WR-975 waveguide. The outputs from two klystrons are fed via 3-1/8 inch coax line into a waveguide hybrid combiner. The signal combines to give a single rf output of at least 100 kW. This signal is fed into the waveguide system to the ATC machine. A directional coupler in one arm in the hybrid combiner provides the information which enables one to adjust the phase and amplitude of each klystron so that it will properly combine. Automatic phase correction loops were not required as the differential phase shifts from each klystron during the pulse were so small that excellent high power combining was achieved. At least 20 dB of isolation was achieved between the two output arms of the high power waveguide combiner under matched load conditions.

HVPS/Energy Storage System

The HVPS used in this system is a three phase, full wave voltage doubler type rectifier circuit. Its nominal output is 25 kV dc with a pulse current rating of 32 amps. Since each klystron requires a current pulse of 8 amps for a period of 20 milliseconds, a capacitive type energy storage system was provided. Each klystron has a capacitor bank of approximately 120 μf and the power supply is common to all four banks and HPA's. A capacitor bank of this size will have a voltage droop during the pulse of approximately 5% and cause an rf power droop of about 12%.

In an effort to simplify the system, a crowbar was eliminated and replaced with a 100Ω current limiting resistor in the klystron cathode circuit and is quite effective in protecting the system.

Non-Technical Aspects

The 200 kW, 800 MHz Lower Hybrid system is a relatively large electronic system. It is peculiar to the field of controlled thermonuclear fusion research only insofar as the long pulse and low duty factor is concerned. The system was designed, constructed and tested wholly at PPPL in approximately 18 months at a cost of about $600K. Tentative long range plans consider this system somewhat as a prototype for a much larger Lower Hybrid system planned for 1978 or 1979.

ACKNOWLEDGMENT

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RF SYSTEM

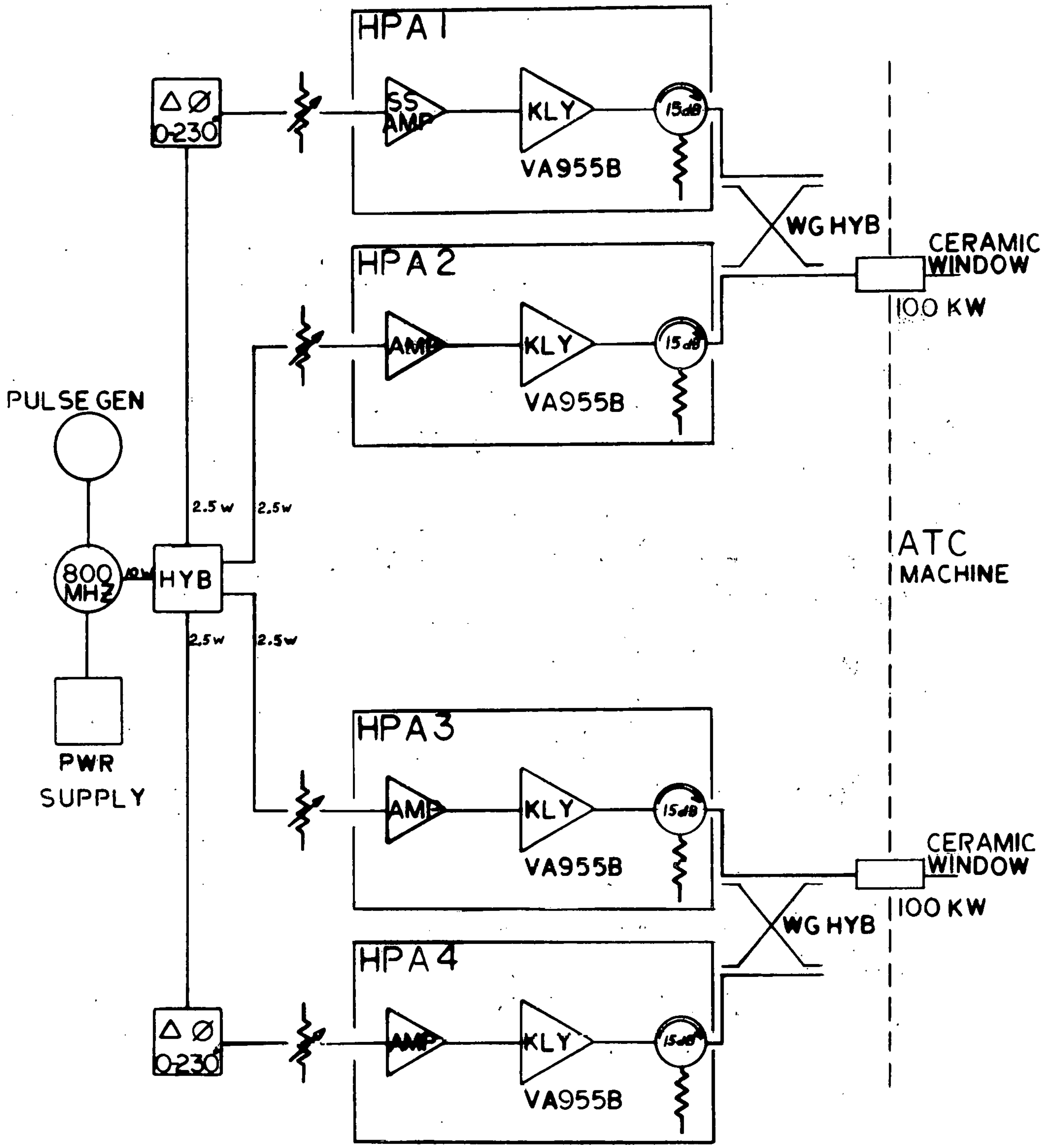


FIGURE 1

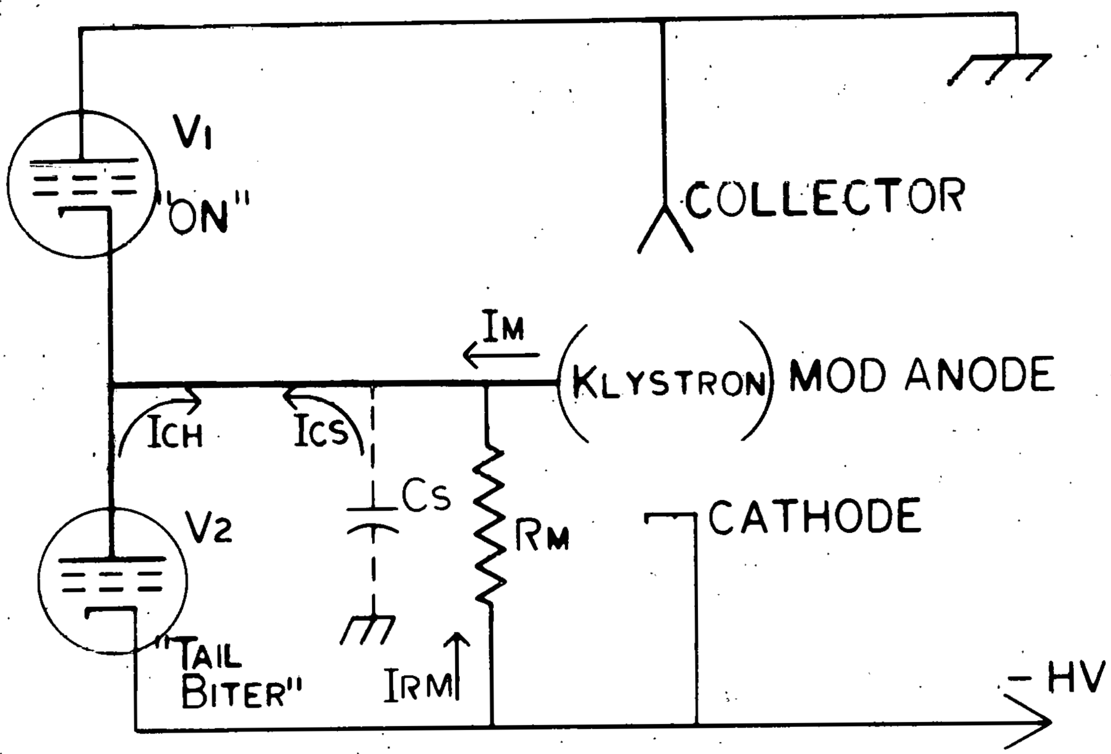
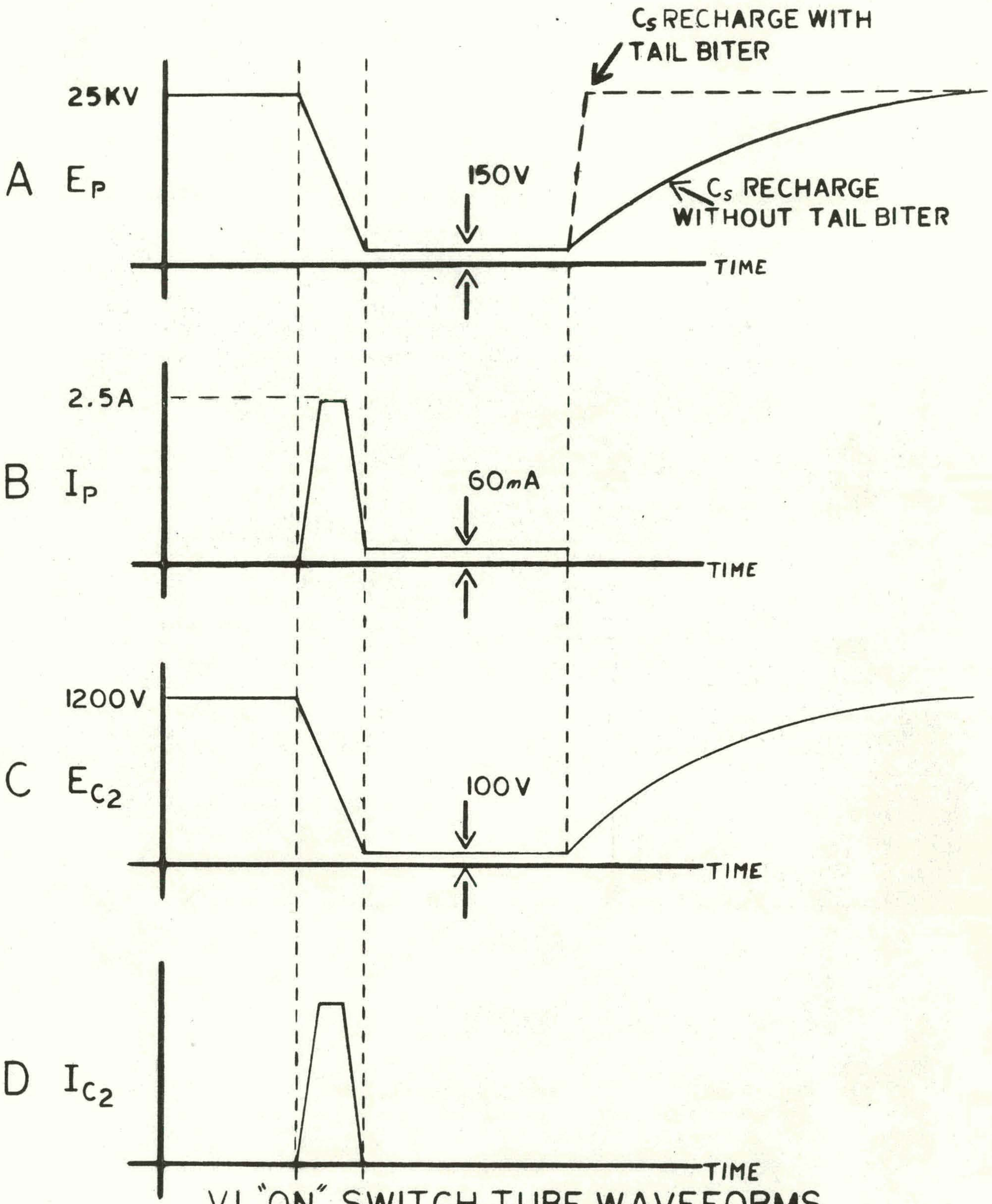


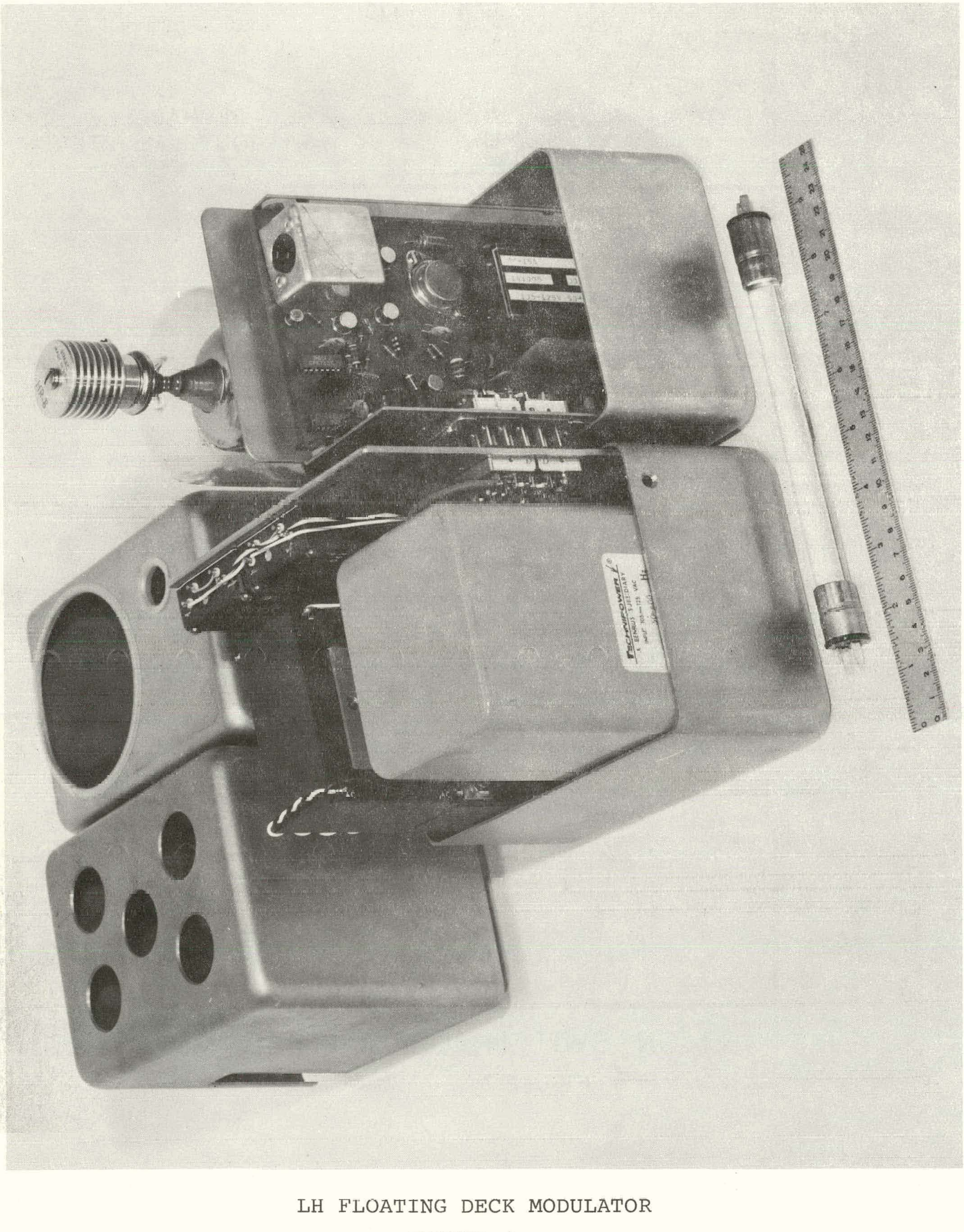
FIGURE 2

FLOATING DECK MODULATOR
AND KLYSTRON (SIMPLIFIED)



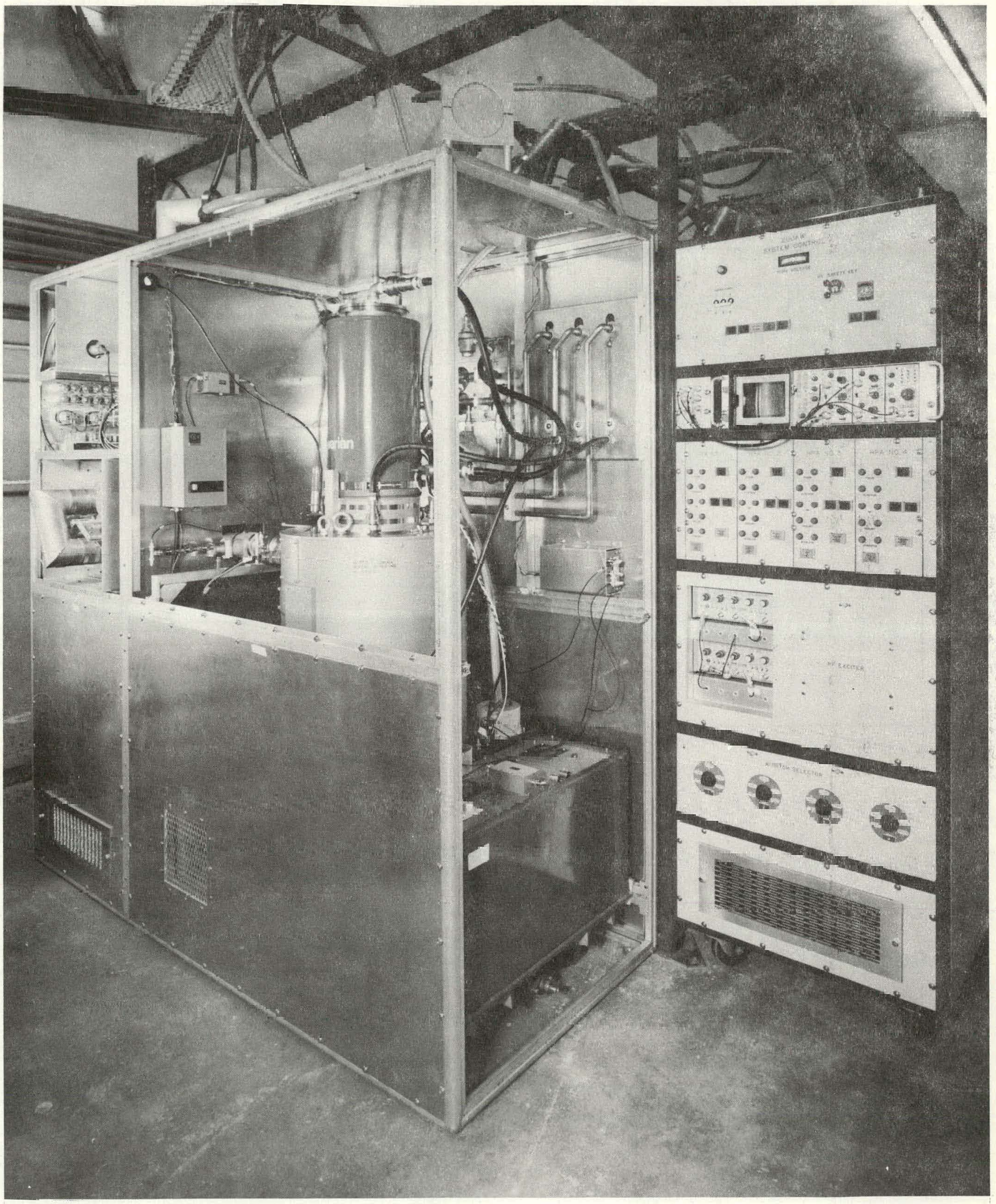
VI "ON" SWITCH TUBE WAVEFORMS

FIGURE 3



LH FLOATING DECK MODULATOR

FIGURE 4



LH HPA AND DRIVER/CONTROL CABINET

FIGURE 5

FAULT DETECTOR (4 CHANNEL)

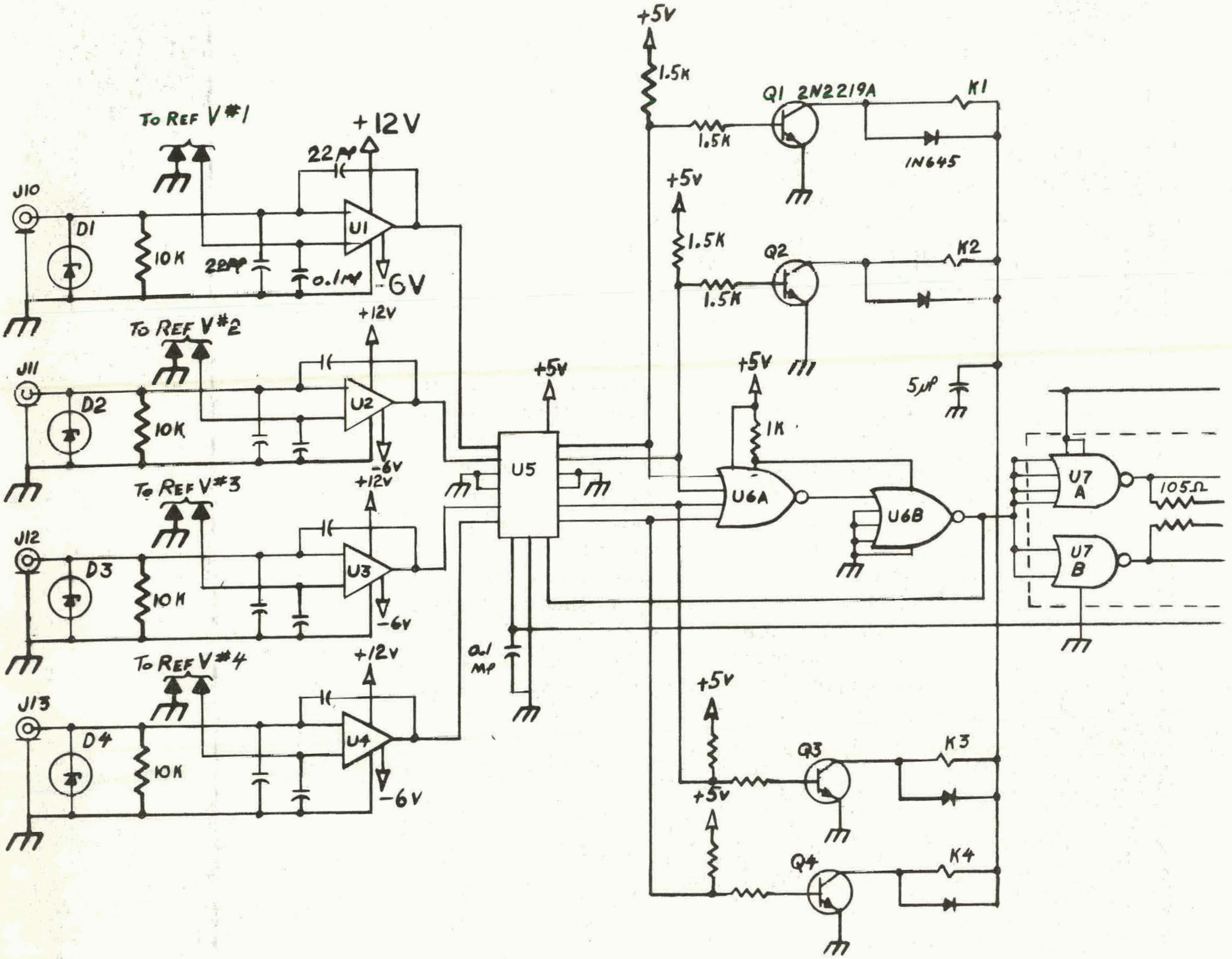


FIGURE 6

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