Octupole Microwave Heating Apparatus and Techniques

by

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I. INTRODUCTION

This note is intended as a convenient summary of descriptions of microwave heating equipment and techniques that have been developed for use with the Wisconsin toroidal octupoles.

II. MAGNETRONS

A. Types and characteristics

Magnetrons and klystrons are vacuum tube oscillators useful for producing high power pulsed or CW microwave signals. They require an external dc magnetic field, filament power, and cathode power. They are operated with their anode at ground potential. The cathode is generally internally connected to one side of the filament and is driven negatively to produce oscillation. The output is either coaxial or waveguide. Table I lists the characteristics of the various types that have been used for actual plasma experiments and represents only a small selection of those available.

TABLE I

Type	f(MHz)	λ(cm)	Filament	Cathode	P_{out}(kW)	τ(μsec)
5J29	400	75				CW
700C	700	43	12.6 V	10 kV@5 A	20	144
5J26	1300	23	12.6 V	22 kV@4 A	40	100
5609	2450	12	6.3 V@3.5 A	1.5 kV@.1 A	0.1	CW
QK254	2900	10.4	12.6 V		100	144
5607	3000	10	5.4 V@18 A	4.5 kV@1 A	2	CW
2J38	3250	9.2	6.3 V@1.25 A	5 kV@6 A	10	288
QK241	5280	5.6	6.3 V@30 A		70	144
VA856B	7600	3.9	8.5 V@5 A	4.5 kV@.4 A	1	CW
6249 A	9000	3.3	9.0 V@15 A	28 kV@8 A	100	100
3J31	24000	1.25	6.3 V			16

B. Operation

The pulse lengths in Table I represent the maximums that have been obtained with low duty cycles without significant derating. These pulsed magnetrons are designed for typical pulse lengths of 1 μsec at 1000 pulses per second, but for the low duty cycles required in the octupole experiments (~1 pulse/minute) it has been found that most of the magnetrons will deliver nearly full power for 100 μsec or longer. Longer pulse lengths can generally be obtained at lower power by reducing the cathode current, and/or magnetic field strength. Magnetrons will not oscillate until the cathode voltage reaches a critical value that is proportional to magnetic field strength, and then the voltage remains relatively constant as the current increases until internal arcing in the tube occurs. The frequency of oscillation is determined by the internal cavity dimensions and is nearly independent of cathode current and magnetic field strength. Some magnetrons are mechanically tunable over a limited range (~10-20%). Magnetrons that have not been run for a long time aften have to be aged by intentionally arcing the magnetron to drive adsorbed gas off the electrodes. The cathode current and pulse length that can be obtained without arcing will slowly increase as a result of this procedure. Low filament voltage will lead to arcing, and high filament voltage reduces tube life. Cathode current and voltage are useful parameters to monitor, and can be used to calculate the input power. Magnetrons are typically 30-50% efficient, and so the rf output power can also be estimated. CW magnetrons or pulsed magnetrons with high filament power ($\gtrsim$ 50 watts) require forced air cooling, although the cooling requirements are not as severe as in the high duty cycle applications for which the tubes were designed. As a general rule, the cooling fins should not become too hot to touch.

C. Associated Plumbing

A ferrite isolator should ideally be connected to the output of all magnetrons to prevent reflected power from unmatched loads from reaching the magnetron. Such reflections increase the cathode dissipation and can cause instabilities in magnetron operation. High power variable attenuators are not common but are useful for adjusting the level of the rf output power. Directional couplers or cross couplers are available that sample foward and reflected power. Their output is a highly attenuated microwave signal. The signal can be converted to a dc level using a microwave diode (1N21B thru 4 GHz, 1N23B thru 12 GHx, 1N78A thru 25 GHz). The diodes work well into a 50 Ω load and produce a voltage that is proportional to power up to a level where they saturate. A dc return path must be provided on the rf side of the crystal if used with an open stub. These components are available in either waveguide or coax. Coax/waveguide transitions are readily available. Coax is much lossier than waveguide at microwave frequencies, although at low frequencies it is much more convenient. Ordinary or special 50 Ω coax makes a good, cheap, low power attenuator for microwaves with an attenuation that increases with frequency. RG8A/U (polyethylene) cable has an attenuation of 8 dB/100 ft at 1000 MHz, and FHJ4 (heliax foam) is about the best coax available with 3 dB/100 ft at 1000 MHz. Waveguide arcing at high power can be cured by evacuation to $\lesssim 10^{-3}$ torr or by pressurization, preferably with sulfur hexiflouride. Windows at the entrance to the vacuum cavity are always a problem. Pyrex and lucite have been used, but quartz is best. When possible, the waveguide should flare out at the entrance to the cavity to produce a good impedance match and to reduce the electric field strength, and the window should be well back in the guide. Two microwave signals of different frequency can be fed into the same waveguide without appreciable loss or reflection by using a duplexer.

D. Ion Heater

Although not in the same class as magnetrons, it is appropriate to mention the 100 kW, 1 MHz pulsed oscillator that is shown in Fig. 1 because it was designed to be operated from the same pulsers used for the magnetrons. It is a high power regenerative oscillator that was designed for ion cyclotron resonance heating. It requires 12.6 V at 6 amps for the filament and -15 kV at 6 amps for the cathode, although it will still produce nearly full power with -5 KV at 18 amps. The output works best into a 50 Ω load, but a loading control permits operation into other impedances at reduced efficiency. It produces 320 μsec pulses at full power, and up to 0.1 sec at reduced power. A 100 kW, 50 Ω delay line network is available for converting the output to 3 phase rf.

III. POWER SUPPLIES

A. Three Channel Pulser

Magnetron power supplies should provide negative dc or rectangular voltage pulses and low voltage, high current ac for the filament. A basic magnetron circuit is shown in Fig. 2. The pulse forming network (high volaage, lumped constant delay line (See PLP 354)) is charged positively from a high voltage dc power supply. A trigger pulse fires the thyratron that discharges the pulse forming network into the primary of the pulse transformer. The transformer steps up the voltage and drives the cathode of the magnetron. Other magnetron pulsers are variations of this basic circuit.

The three channel magnetron pulser is a versatile circuit that is capable of providing filament power and pulsed dc up to 45 kV. Up to 600 joules can be stored in a bank of 45 pulse forming networks which are each rated at 15 kV dc, have an impedance of 67 Ω and produce a 16 μsec rectangular pulse when discharged into a matched load. They can be connected in series to produce pulses up to 720 μsec or in parallel to match impedances down to 1.5 Ω.

Channel 1 contains a 6.3 V, 5 amp filament transformer. It has no pulse transformer, but has an internal 75 Ω load resistor, and so can deliver pulses of arbitrary length at up to 7.5 kV. It has been used primarily with the 2J38 magnetron, for which the HV should be set to 9.0 kV. Channel 2 has a filament transformer that can be connected with jumpers in the rear to provide up to 12.6 V at 22 amps or 6.3 V at 44 amps. It has a 1:6 pulse transformer that saturates at 3.4 V-seconds on the secondary. Reverse biasing the transformer with the built-in cocking circuit extends the pulse to 4.8 V-seconds. Filament current is provided through a tri-filar winding on the secondary. This channel is used for all the magnetrons that require > 7.5 kV cathode voltage. Channel 3 contains neither a filament transformer nor a pulse transformed, and so it is capable of providing ≤ 7.5 kV to a magnetron or other device not requiring or having its own filament transformer.

Figures 3-6 show circuits for the various components of the pulser. A three channel timer (described in PLP 179) provides pulses to the thyratron grids and permits up to three magnetrons to be pulsed simultaneously or in sequence. The HV supplies are regulated against line voltage variation and are overload protected. A three minute time delay and door interlock interrupt ac to the supplies and drop the shorting bar, discharging the pulse networks. Magnetron voltage and current can be sampled from the front panel. Outputs are 1 V/kV and 1 V/amp into an unterminated cable (or 0.5 V/kV and .98 V/amp into a 50 Ω load).

B. 144 μsec Magnetron Pulser

A separate self-contained pulser similar to channel 1 of the three channel pulser has been constructed primarily for use with the small octupole while the three channel pulser is in use at PSL. It produces 144 μsec pulses at voltages up to 7.5 kV. It has two, parallel, easily removable, 125 Ω resistors connected internally across the pulse output. It has a filament supply capable of 14 V @ 5 A. It was designed for use with the 2J38 magnetron, although it has also been used with the 1 MHz oscillator at only slightly reduced power. It will accept a + 12 or + 300 volt trigger pulse, and has provision for monitoring pulse voltage and current. The circuit is shown in Fig. 7.

C. 0.1 sec Klystron Pulser

The pulser circuit shown in Fig. 8 is different from those previously discussed in that the energy is stored in a large capacitor bank (120 μF @ 10 kV) that is momentarily switched to the load by means of a vacuum relay. A 500 Ω series resistor limits the current to 20 A in the event of an arc. The capacitor is sufficiently large that for pulses of ≤ 0.1 second, the capacity voltage does not change appreciably and a nearly rectangular voltage pulse results. The filament supply is capable of providing 12.6 V @ 6 A. The circuit was designed for use with the VA 856 B klystron, although it has been used with the 5607 magnetron and with the 1 MHz ion heater. There is a delay of ~ 5 msec after the trigger pulse is applied before the relay closes. The pulse length is adjustable from ~ 10 - 100 msec by an internal timer. The relay bounces slightly on both the open and close operation. A new tube pulser is being constructed to eliminate pulse droop and relay bounce.

D. 100 Watt CW Magnetron Supply

The magnetron circuit of Fig. 9 has been used extensively with the PSL octupole because of its simplicity and reliability. It is a self contained circuit requiring only 115 VAC and producing 100 watts at 2.45 GHz at the coaxial output. It has a built-in RK 5609 magnetron. The magnetron output is roughly proportional to magnetron current and can be adjusted from ~10 to ~100 watts by a variac on the front panel. It can be run continuously or switched on for a few seconds while the multipole pulses, using the remote trigger jacks on the panel. A rapid turn-off circuit is included. It consists of a thyratron that drops the magnetron cathode voltage to half value through a set of capacitors. The rf power thus turns off abruptly and slowly comes back on after ~ 50 msec. This feature is useful for observing the decay of the plasma in the afterglow. It has a three minute time delay and a cathode overcurrent relay that should be set for ~ 135 MA.

IV. PLASMA EXPERIMENTS

In this section, the major results of experiments on microwave heating in toroidal multipoles will be summarized in a few short paragraphs.

A. Microwaves injected into a confinement device with conducting walls will produce a plasma if electron cycltron resonance occurs within the cavity and if the neutral gas pressure is sufficiently high that the microwave pulse length is several times the ionization time, where

$$\tau_i(\text{sec}) \simeq 10^{-9}/p(\text{torr}) \quad \text{(for hydrogen)}.$$

The density of the plasma thus obtained increases linearly with microwave power up to some saturation value that increases with the square of the microwave frequency.

B. For short microwave pulses ($\ll \tau_i$) or for low pressure, the microwaves have no effect unless a background plasma is present, produced, for example, by gun injection or by CW microwave heating. In this case, the average electron energy increases to some value that depends on pulse length, microwave power, and loss mechanisms. The heating is strongest if electron cyclotron resonance occurs in the cavity, but weak upper off resonance heating has also been observed. The upper off resonance heating rate increases linearly with plasma density and microwave power, and is strongest when the temperature of the background plasma is high. The electron distribution function during resonant heating is anisotropic and has the form

$$f(W) = \frac{3n}{\overline{W}} \; e^{-\sqrt{6W/\overline{W}}}$$

on the separatrix, and rapidly decays to a lower energy maxwellian after the heating is turned off. The electron heating is strongly localized in regions where $dB/d\ell = 0$ at resonance, particularly if resonance occurs at a local minimum in $B(\ell)$.

C. Energetic electrons are cooled primarily by ionization and by obstacle loss. For ionization,

$$\frac{d\overline{W}}{dt} = - \frac{\overline{W}}{\tau_i} \quad \text{and} \quad \frac{dn}{dt} = \frac{n}{\tau_i}$$

and for obstacles,

$$\frac{d\overline{W}}{dt} = - \frac{-v_i A\overline{W}}{V} \quad \text{and} \quad \frac{dn}{dt} = - \frac{\overline{v}_i An}{4V},$$

where n is the density, A is the obstacle area, V is the volume of the device, and $\overline{v}_i$ is the average ion thermal velocity (or ion acoustic velocity for $T_i < T_e$). Above a certain density given approximately by

$$n \simeq \frac{\varepsilon_o m\omega^2}{Qe^2},$$

the microwave energy is totally absorbed by the plasma, and the average energy therefore decreases with increasing density. Below that density, the heating rate can be calculated from

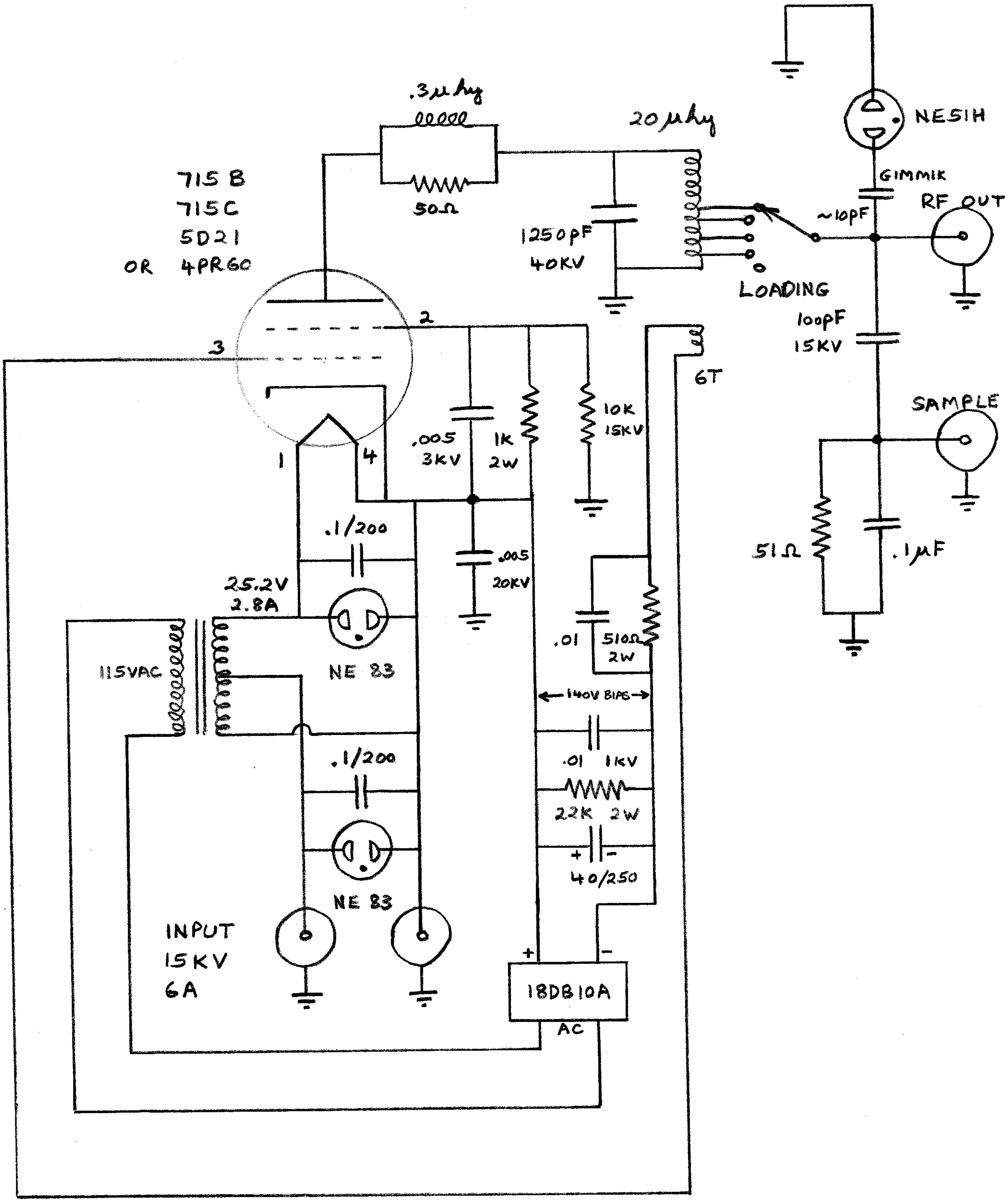
$$\frac{d\overline{W}}{dt} = \frac{\pi}{3} e\overline{E^2} \frac{1}{V'} \frac{d^2V}{dBd\psi}\bigg|_{B_o} \simeq \frac{e\overline{E^2}}{B_o},$$

where $\overline{E^2}$ is the mean square microwave electric field and B_o is the value of the magnetic field at resonance. Some evidence for ion heating has also been observed.

D. The plasma produced by microwave heating at high pressure is very reproducible and consists of a cold ion (.025 eV < kT_i < kT_e), and a warm electron (kT_e ~ 0.1 - 10 eV) component. The initial density distribution can be easily changed by changing the magnetic field strength and/or the microwave frequency, thereby moving the resonance zones. The plasma is necessarily produced away from the B = 0 axis, but it rapidly collapses to fill the region near the separatrix. The subsequent behavior of the plasma in the afterglow resembles that of a gun injected plasma except for its longer lifetime and more rapid cooling due to the high background neutral pressure. Details of the evolution of the density profile and of fluctuations observed are contained in PLP 282.

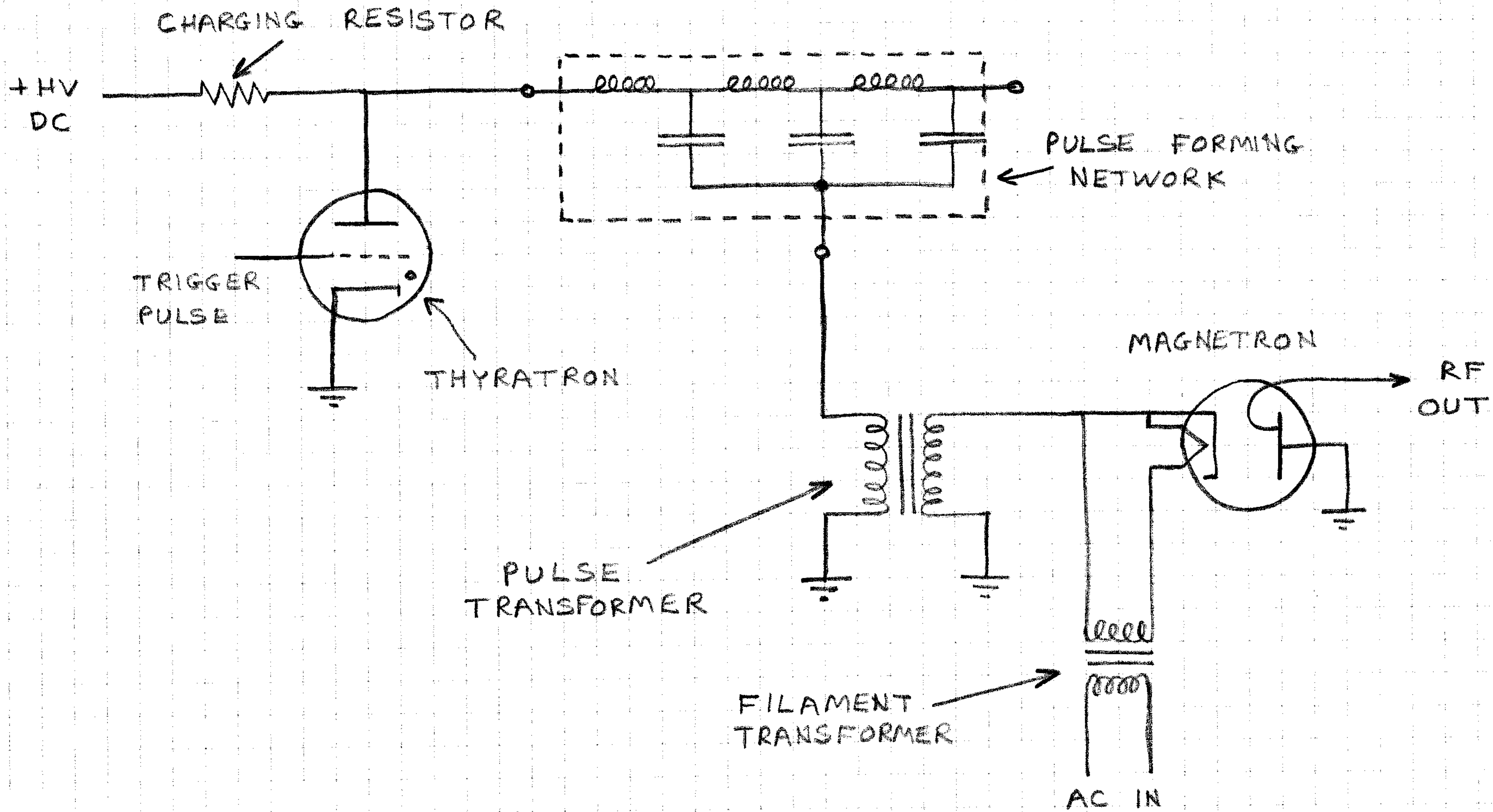
ACKNOWLEDGMENTS

Much of the microwave apparatus was developed by Paul Nonn who is also an inexhaustible supplier of components and information. Tom Lovell has also assisted in much of the development.

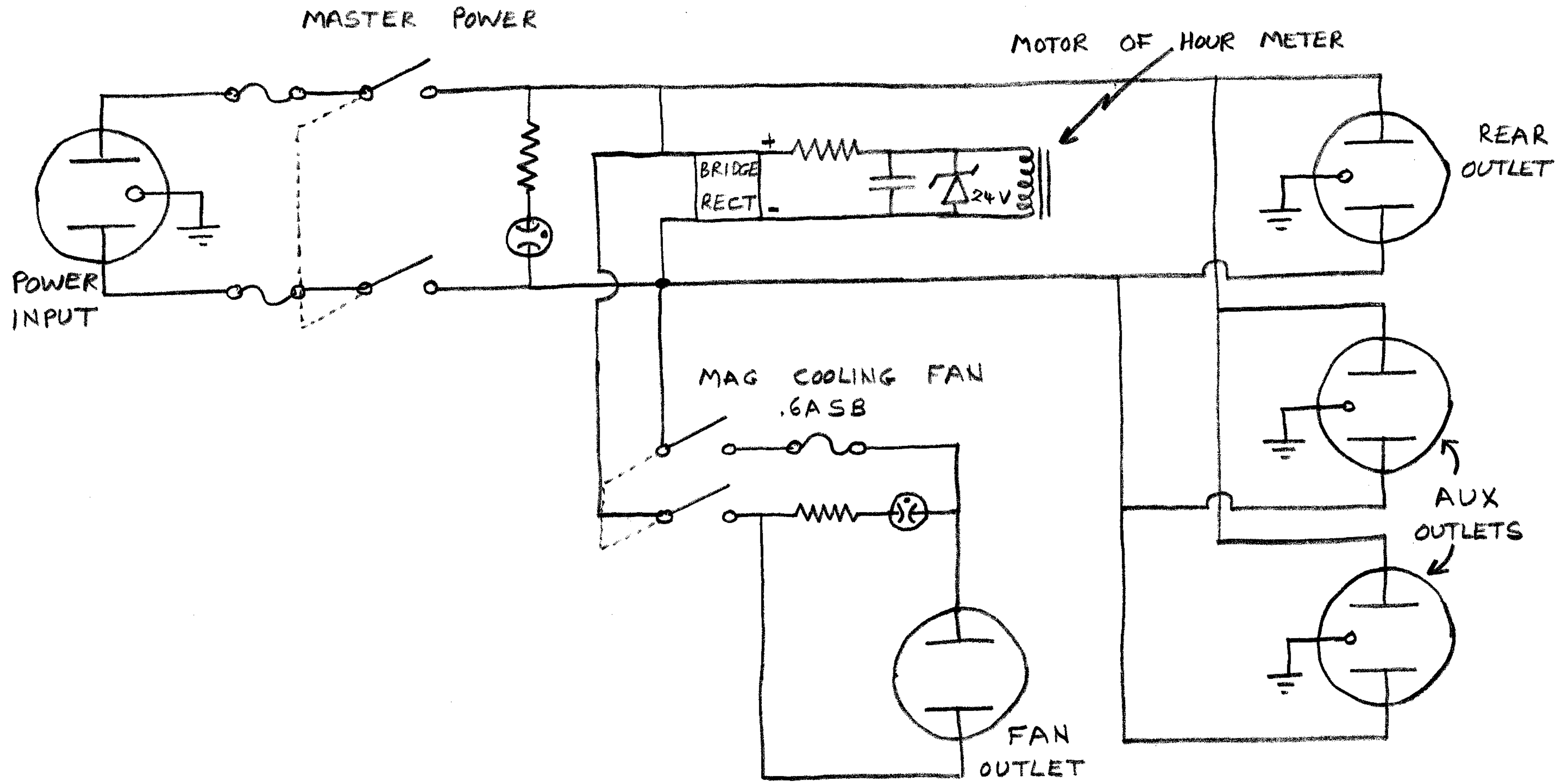


SPROTT SUPER ION HEATER

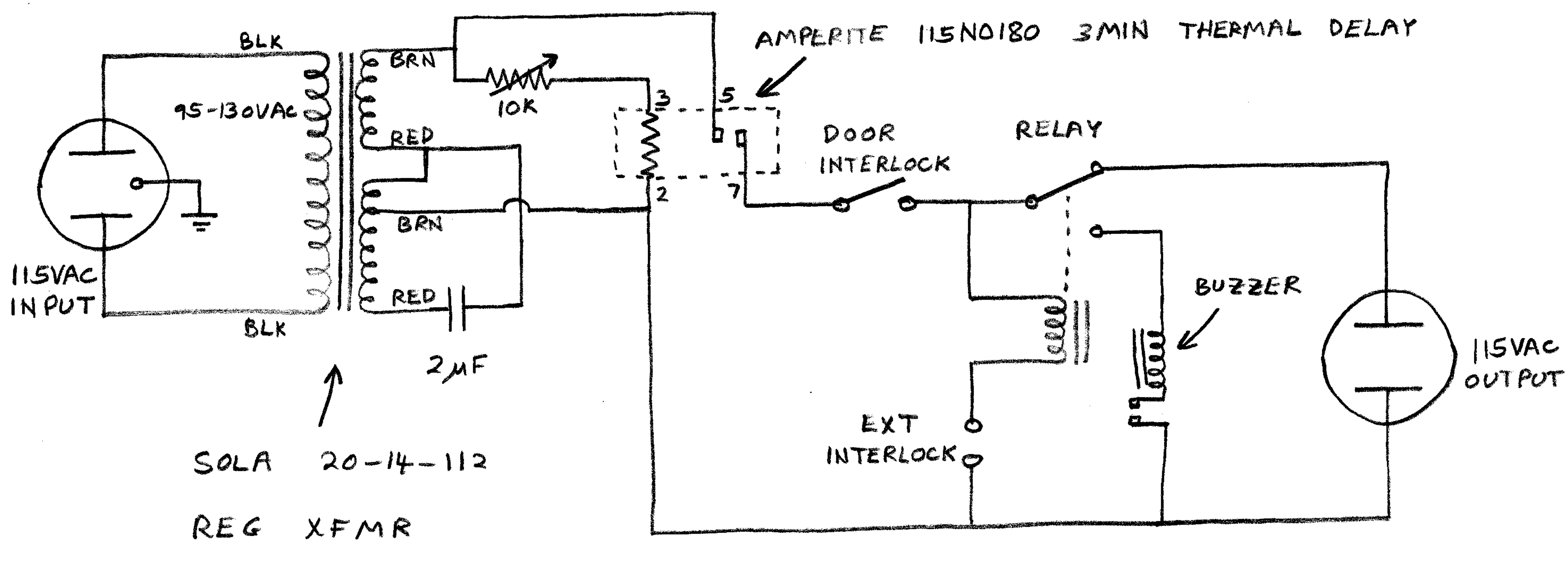
100 KW AT 1 MHZ



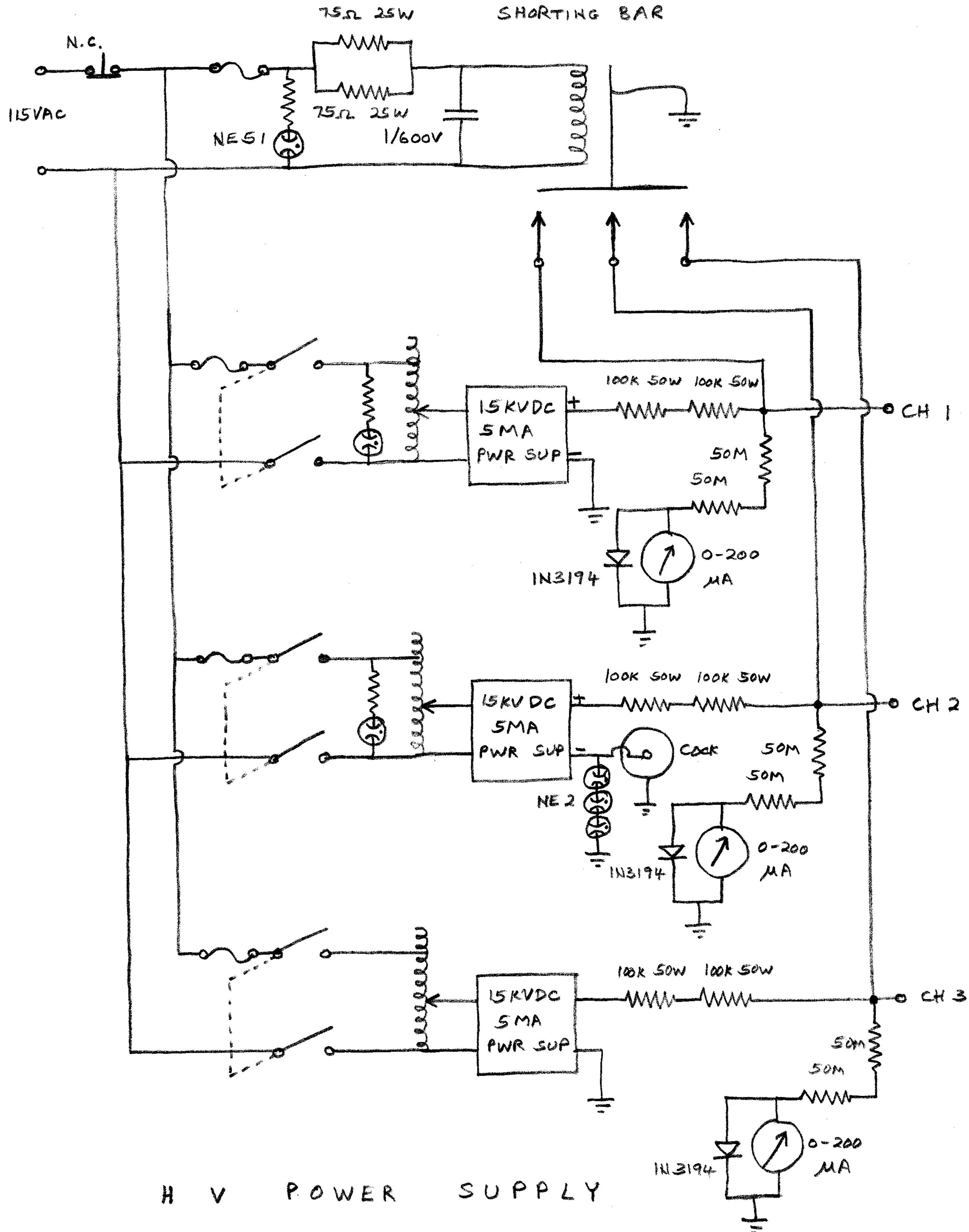
BASIC MAGNETRON CIRCUIT



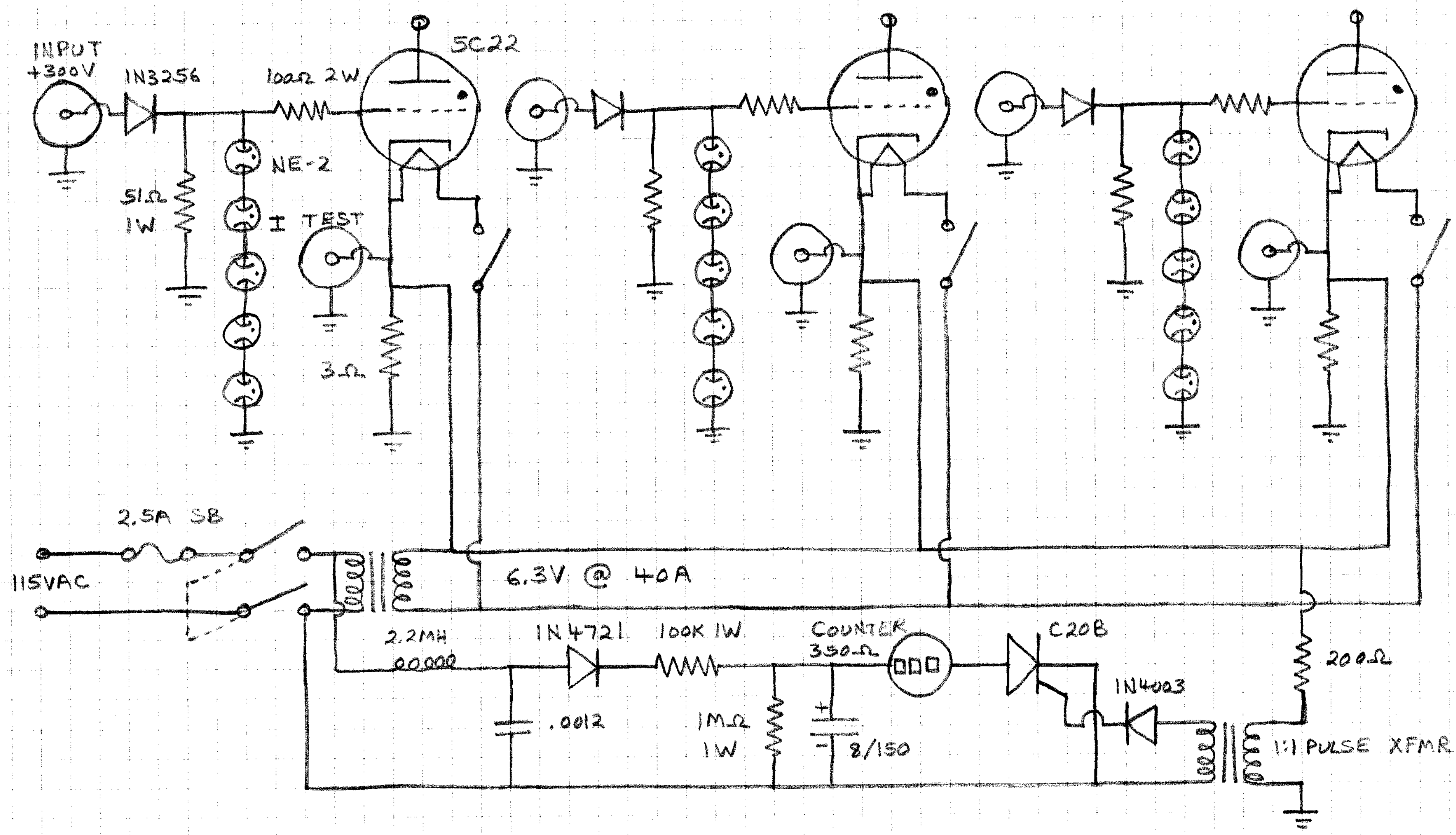
POWER DISTRIBUTION PANEL



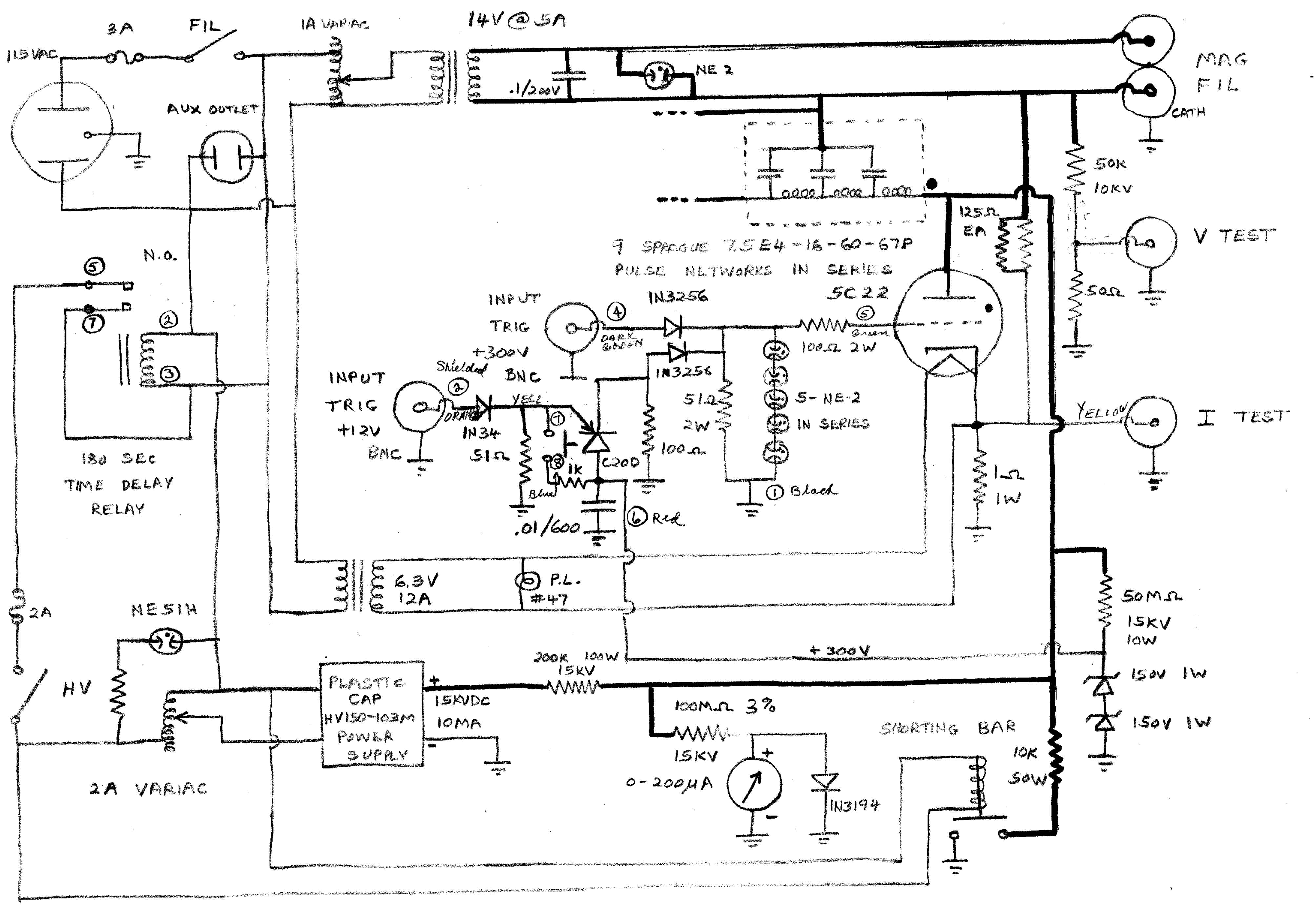
H. V. SUPPLY REGULATOR AND INTERLOCK CKT



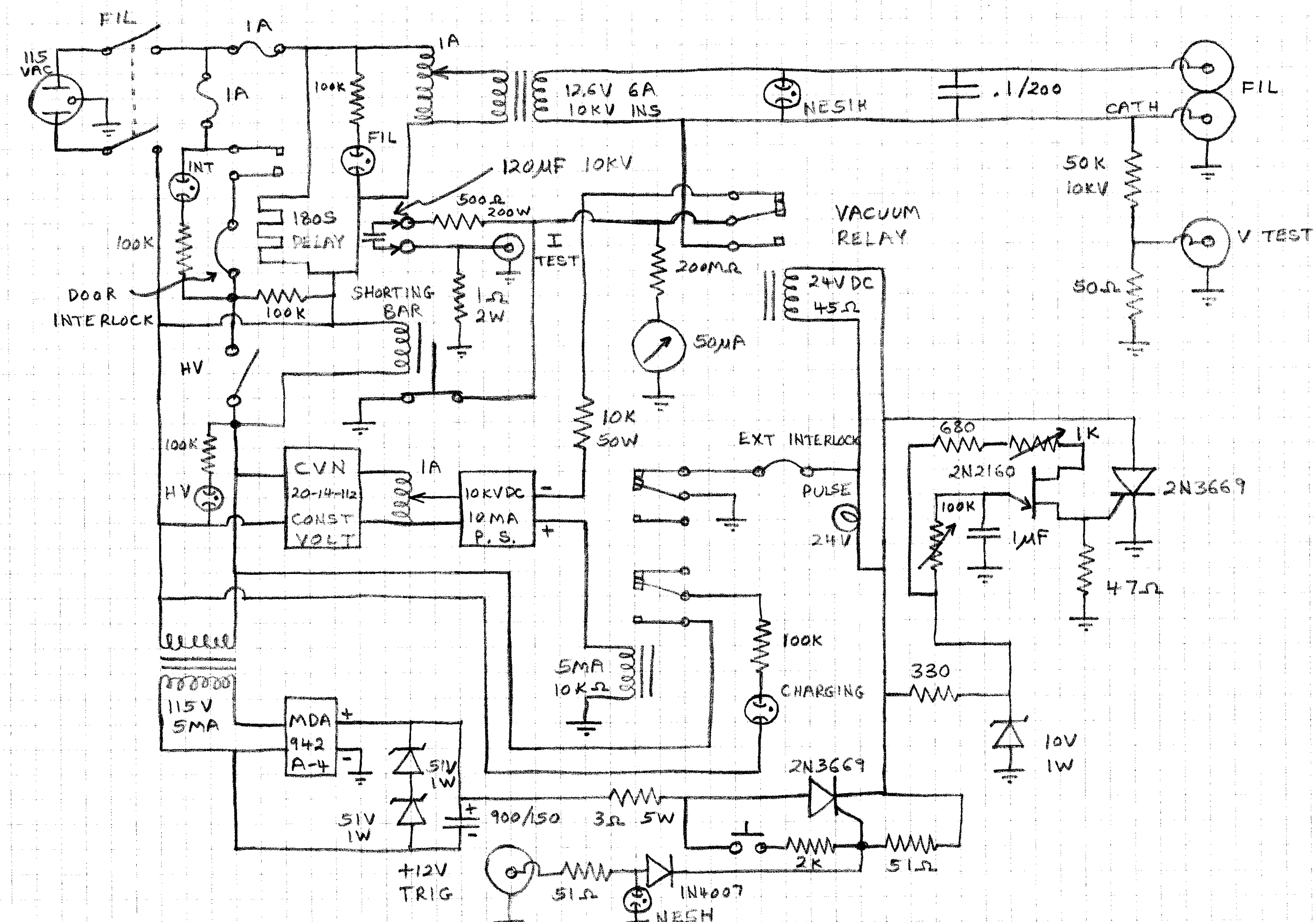
H V POWER SUPPLY



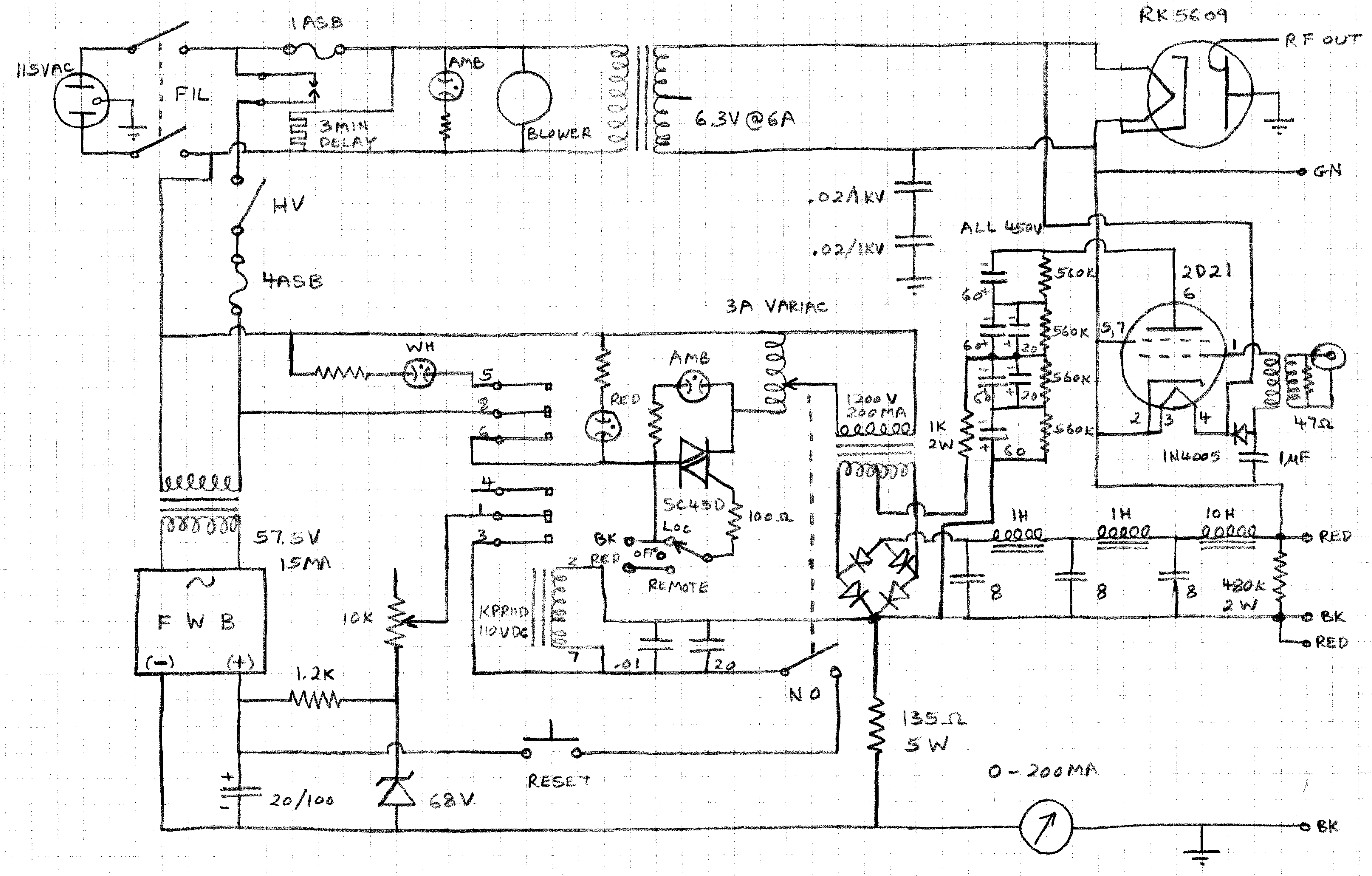
THYRATRON PULSER - PULSE COUNTER



144 μSEC MAGNETRON PULSER UNIT



0.1 SECOND KLYSTRON PULSER



100 WATT CW MAGNETRON POWER SUPPLY