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NRL REPORT 3501

FR-3501

THE INVESTIGATION OF HIGH-RESOLUTION RADAR PHENOMENA

PART I - SHORT-PULSE TRANSMITTER

DECLASSIFIED: By authority of
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No. [redacted] 14-61 2 May 61
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THE INVESTIGATION OF HIGH-RESOLUTION RADAR PHENOMENA

PART I - SHORT-PULSE TRANSMITTER

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July 8, 1949

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CONTENTS

ABSTRACT

The development of a short-pulse transmitter which produces video and r-f pulses of 0.013-microsecond to 0.1-microsecond duration is described. A summary of design criteria is included.

PROBLEM STATUS

This is an interim report on this problem; work is continuing.

AUTHORIZATION

NRL Problem R12-02R

THE INVESTIGATION OF HIGH-RESOLUTION RADAR PHENOMENA
PART I - SHORT-PULSE TRANSMITTER

PROBLEM ANALYSIS

The resolution of a radar system may be improved by a reduction in either antenna beamwidth or pulse duration since variations in either change the ratio of target volume to pulse volume. An attempt to reduce the pulse duration an order of magnitude below present operating limits led to the development of a 0.01-microsecond transmitter.

The analysis of the problem of generating short r-f pulses involves the formation of a d-c pulse of the proper duration, the coupling of this pulse with minimum distortion to the magnetron, the generation of an r-f pulse of proper bandwidth by the magnetron, and the isolation of this r-f pulse from the receiver. Since limitations exist in the performance of the pulse generator and the magnetron, a balance is desired between the minimum pulse width which it is possible to generate and the bandwidth obtainable in the magnetron.

Pulse Generation

One of the most important design considerations of a short-pulse modulator is the rise and fall time of the pulse, since, if a reasonably square pulse is desired, the rise and fall time must be in the neighborhood of a few thousandths of a microsecond. This demands the use of time constants of the order of 10^{-9} seconds which must be determined largely by the operating impedance of the circuit since the stray capacity of the circuit is roughly a constant. This operating impedance, in combination with the pulse voltage desired, will determine the current involved and give an idea of tube requirements. Since magnetrons require roughly 10^4 volts, the peak currents involved will be approximately 10^2 amperes. Such currents may be handled in two ways. One method is to use several hard tubes in parallel, which adds considerable stray capacity to the circuit and forces the design to a still lower operating impedance. The other solution is to use a single gas tube, which introduces a probable source of jitter. The latter solution appears more attractive providing the jitter can be held to a usable minimum. The high currents involved demand a current source, such as a charged condenser or a delay network. Here the use of the delay network or line is indicated because of its inherent suitability for the formation of square pulses. These two requirements lead directly to the choice of a line-type modulator using a hydrogen thyratron.

Coupling

Once the pulse is formed, it is necessary to couple this pulse to the magnetron. The pulse length considered here eliminates the use of a pulse transformer as a coupling device since the transformer bandwidths at present available are insufficient to handle the frequencies involved. Accordingly, a means of coupling the modulation directly to the magnetron must be devised.

Magnetron Requirements

Consideration must next be given to the operation of the magnetron. The normal requirement that the time consumed by the build-up of oscillations be a small fraction of the total oscillation time places a severe requirement on the magnetron when the pulse duration is as short as that considered here. This build-up may be interpreted in terms of the r-f bandwidth of the magnetron, and from the characteristics of available magnetrons it appears that a magnetron with a small C/L ratio operating on the lowest possible voltage should have the best possibilities.

Receiver Isolation

Obtaining the required receiver isolation also presents a problem since a preliminary examination of the TR and ATR possibilities indicate that the available TR'S and ATR'S do not fire fast enough to provide proper isolation in the case of a 0.01-microsecond r-f pulse. The possibility of using two separate antenna feed horns, side by side, for transmitting and receiving offers a possible solution since the isolation in the E-plane of these horns is in the neighborhood of 35 db. This would be adequate for low-power magnetrons but the limitations of antenna design introduced make it undesirable.

EXPERIMENTAL SOLUTION

A modulator capable of developing a pulse 0.01 microsecond in width and 6 to 10 kv in amplitude, over a pulse repetition frequency (prf) range of 100 to 3500 cycles is shown in Figure 1. This gives 15 kw of r-f peak power when modulating a 2J42 magnetron. The theory of operation is as follows: A positive pulse of approximately 200 volts in amplitude and 3 microseconds in width is used to trigger a 5C22 hydrogen thyratron which discharges a 3-foot section of RG77/U 50-ohm pulse cable into a 100-ohm noninductive resistor. The 2J42 magnetron is placed across this 100-ohm resistor; and, since the line is initially charged to approximately 12 kv, the triggering of the gas tube presents a negative pulse of somewhat less than 8 kv (100/150 x 12 kv) on the magnetron cathode. This system makes the modulator very inefficient; but, because of the bandwidth required, it appeared to be a logical solution to the coupling problem, since a pulse transformer of the required bandwidth would be difficult to design with present transformer iron.

The length of the pulse delivered by the modulator can be calculated rather accurately from the length and the velocity constant of the line. Short leads are, of course, necessary since lead-length inductance and capacity can alter the pulse shape. An example of the magnitude of stray inductance and stray capacity involved was that the ten, 10-ohm 2-watt resistors, connected in parallel to form the 1-ohm viewing resistor in Figure 1, introduced sufficient distortion to completely alter the pulse as it appeared on the viewing scope. This distortion was corrected by using a silver band, plated on the noninductive resistor as will be shown in Figure 6.

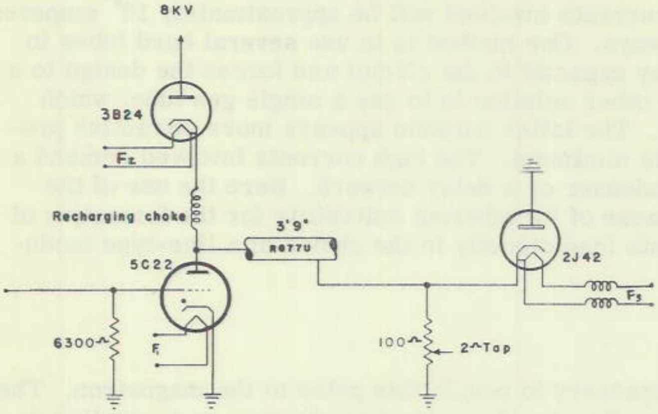


Figure 1 - Short-pulse modulator and magnetron

The time jitter* of the modulator pulse with respect to the viewing scope was in the neighborhood of 0.001 microsecond when the filaments of the gas tube were operated on d.c., and the impedance of the trigger source was below 100 ohms. The modulator voltage pulse as developed across the 100-ohm load resistor had a rise time to the 3-db points of 0.007 microsecond as will be shown in Figure 14 and fall time about the same. This rate of current rise of 6000 amperes per microsecond exceeds the JAN specifications for the 5C22, but no visible effects were noticed in modulator operation. Figure 14 also shows the effect of mismatching the 50-ohm pulse line. An increase in the terminating resistor, in this case the modulator load resistor, results in an increase in pulse amplitude, but it is also accompanied by a step on the trailing edge. In this case, the step is low enough in amplitude not to interfere with the magnetron operation. This increase in pulse voltage for a lower over-all voltage enables the 5C22 to operate at a lower voltage during and immediately after forming the 0.01 microsecond pulse, thus reducing the plate dissipation of the tube. A source of energy dissipated in the 5C22 after forming the pulse was the energy in the charged stray capacity of the charging choke. A lower operating voltage reduces the amount of this energy absorbed in the gas tube.

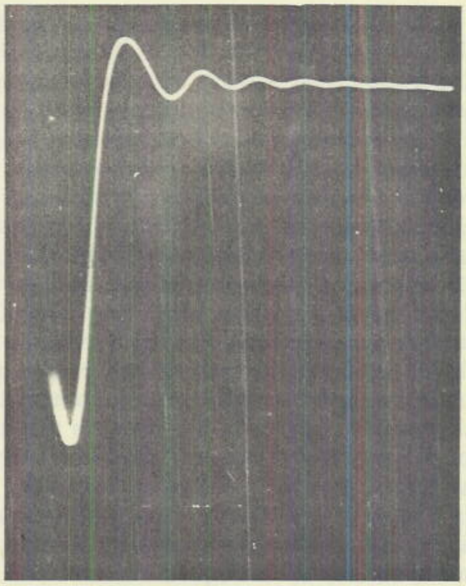


Figure 2 - Charging cycle at plate of 5C22 - sweep length 2000 μsec

In circuits where a hydrogen gas tube is employed, it is necessary to keep the voltage on the plate of the tube within a few hundred volts of ground for a period of at least 25 microseconds after the tube is fired in order for the gas to recover; otherwise, the tube would stay in conduction. The time constant necessary to do this in the case of a resistance-charging modulator is of such a value that the prf is limited to a low value. In order to increase the prf, it is necessary to bring the plate of the gas tube to B+ rapidly after the proper time at low voltage has elapsed. Considerable experimentation with circuits designed to decrease this recovery time led to the choice of the resonant charging-circuit employed. A line capacity of 100 micromicrofarads demands a large choke in order to keep the voltage on the 5C22 at a low value for 25 microseconds; for a maximum prf of 3500 cycles the choke must be 50 henrys. The rate of charging, which can be seen in Figure 2, was determined principally by the combination of inductance and stray capacity of the choke, since the latter was larger than the line capacity. Also, since the charging circuit was to be operated at a frequency relatively high for a 50-henry choke, losses (such as core loss) made it relatively inefficient. The lowest prf at which the modulator could operate was below 100 cycles. A difficulty arises in operating at a low prf in that the charge in the line decays through the tube resistance path. This had to be overcome by increasing the operating voltage.

A 2J42 magnetron with its filaments isolated by a counterwound choke was connected directly to the 100-ohm load resistor. This choke was wound carefully to keep the stray capacity to a minimum and the inductance as high as possible, and still retain the current-carrying capacity required for the magnetron filament current.

A future report will discuss the variation of jitter with regard to trigger characteristics.

Preliminary calculations of the bandwidth of the 2J42 magnetron—based on the unloaded Q of the magnetron, the magnetron C/L ratio, the impedance of the waveguide into which the magnetron works, and the coupling coefficient—indicated that the spectrum bandwidth would be only 150 megacycles wide to the first nodes. To verify this, a TS-148 was modified by adding a separate 200-Mc amplifier and converter in series with the regular r-f section and its 22-Mc, i-f amplifier. Also, by testing a large number of klystrons, one with a 150-Mc mode was located and this was used in the TS-148. In the examination of the r-f spectra, both the klystron cavity and the repeller voltage were varied manually simultaneously to allow viewing of spectra wider than the 150-Mc mode of the klystron. By the use of this equipment, it was determined that the maximum bandwidth obtainable from the 2J42 magnetron, was 163 Mc, which corresponds to the r-f bandwidth associated with a pulse 0.013 μsec in duration. Accordingly, the application of pulses shorter than 0.013 μsec to the magnetron produced no further increase in spectrum width. Since no other magnetron with better characteristics is at present available, this bandwidth limitation must remain in the system and the minimum pulse length is limited to 0.013 microseconds. The final modulator is shown in Figures 3 to 6 and the accompanying power supply is shown in Figures 7 and 8. The spectrum analyzer as modified by this problem, is shown in Figure 9. The pulse measurements shown here were made on the Davis-scope, a special scope having sweep speeds as fast as 100 inches per microsecond. This instrument is shown in Figure 10, and will be completely described in a later report.

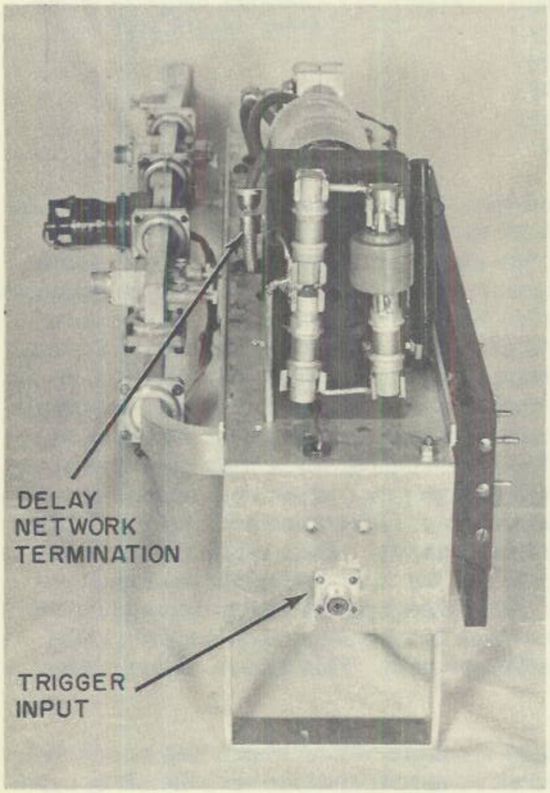


Figure 3 - Transmitter left end

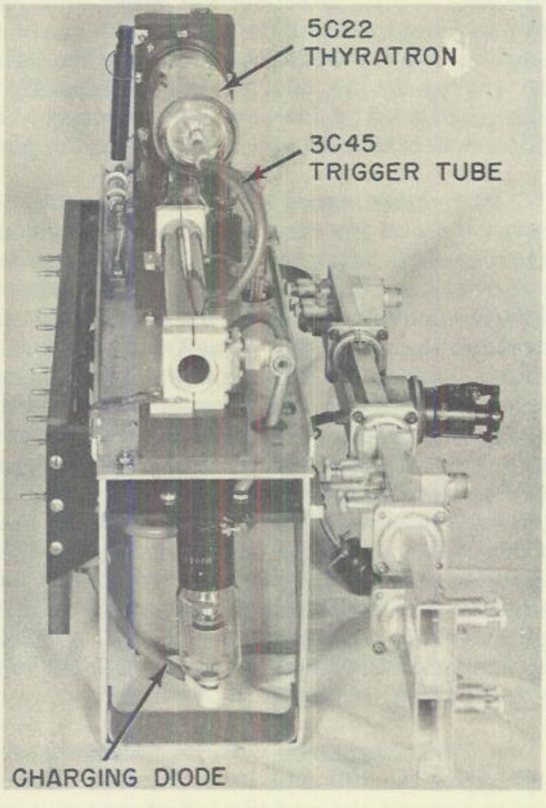


Figure 4 - Transmitter right end

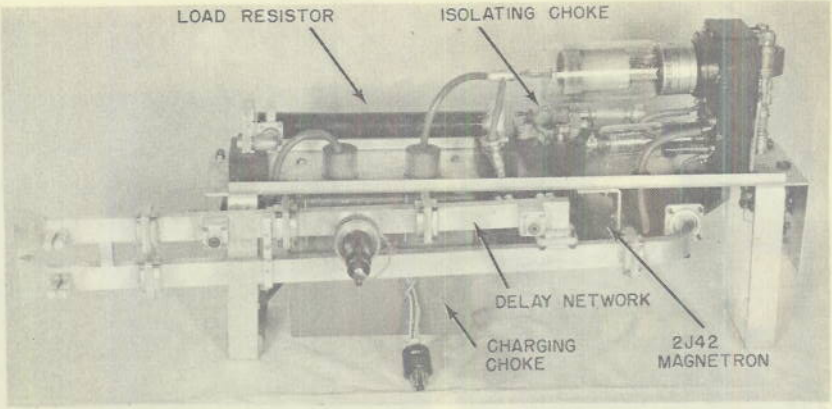


Figure 5 -
Transmitter back

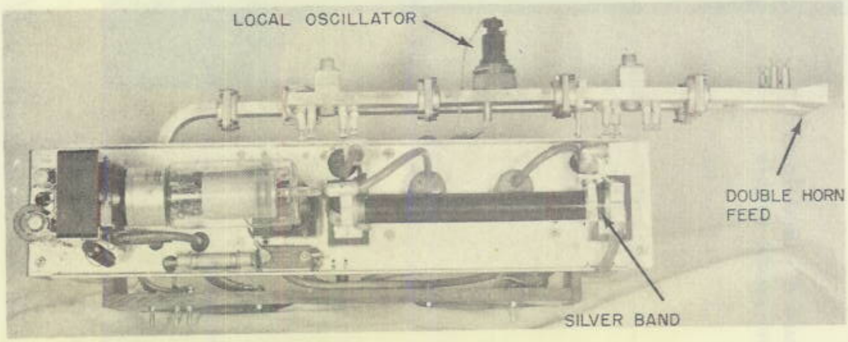


Figure 6 -
Transmitter top

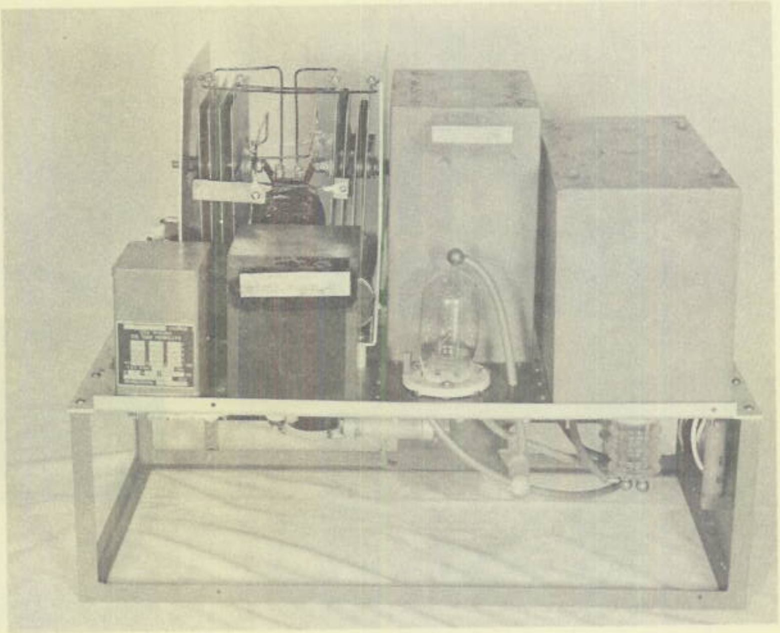


Figure 7 -
Modulator power supply

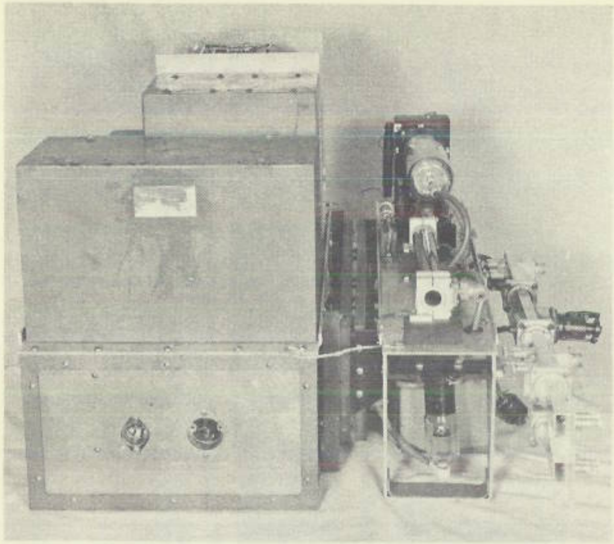


Figure 8 - Modulator and power supply

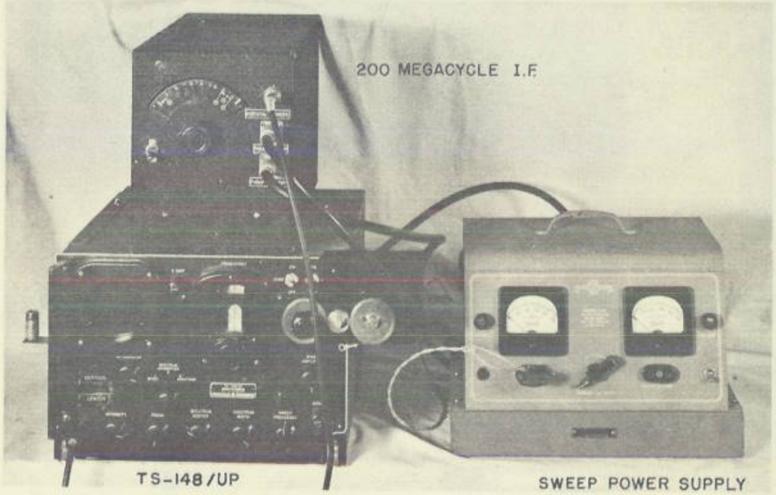


Figure 9 - Modified spectrum analyzer

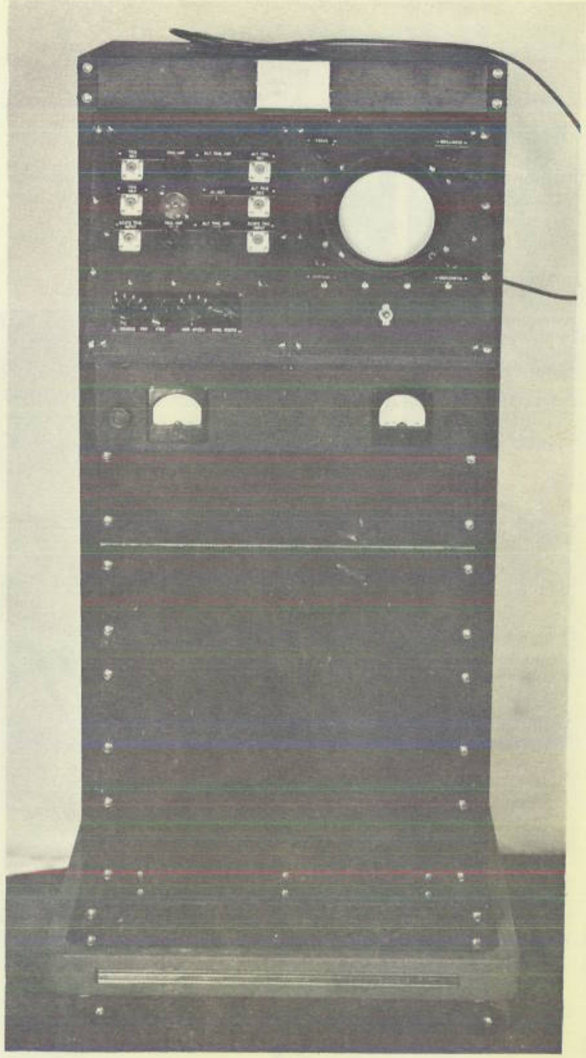


Figure 10 - High-speed Davis-scope

MODULATOR PERFORMANCE

The voltage pulses generated by the modulator and the accompanying r-f spectra are shown in Figures 11 to 18. Figures 11, 12,14, 15 and 17 show the voltage pulses on fast sweeps of 0.05 μ sec and slow sweeps of 0.13 μ sec. Figures 13, 16 and 18 show the r-f spectra for the various voltage pulses. The effect of the magnetron bandwidth is clearly illustrated in Figures 13 and 16 since there is no increase in spectrum width for a reduction in pulse width from 0.013 to 0.01 μ sec. However, a further increase in pulse width to 0.038 yields an r-f spectrum 55 Mc in width.

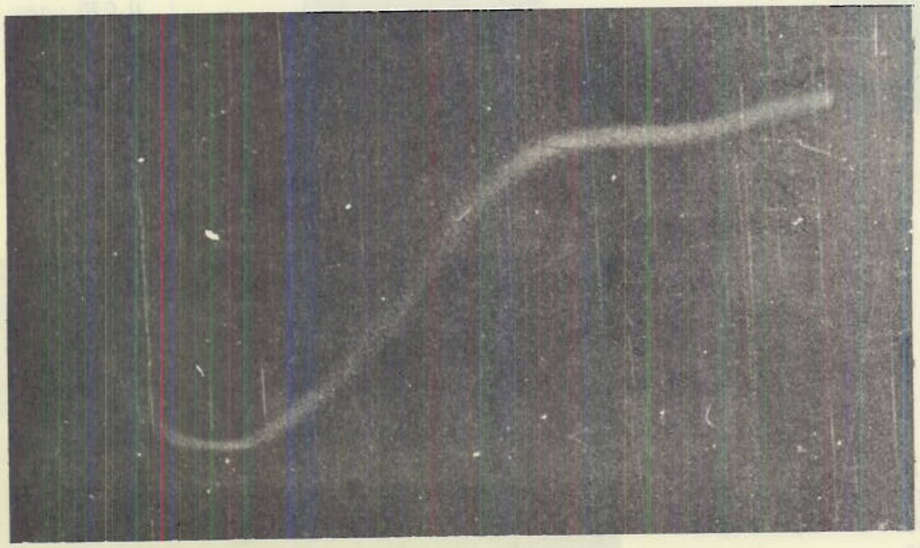


Figure 11 - Voltage pulse - 0.010 μsec - sweep length 0.05 μsec

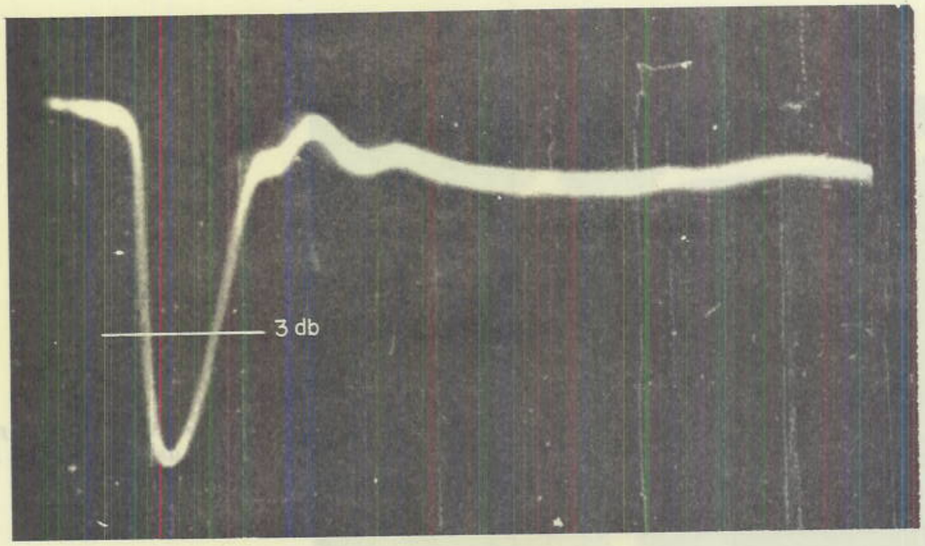


Figure 12 - Voltage pulse - 0.010 μsec - sweep length 0.13 μsec

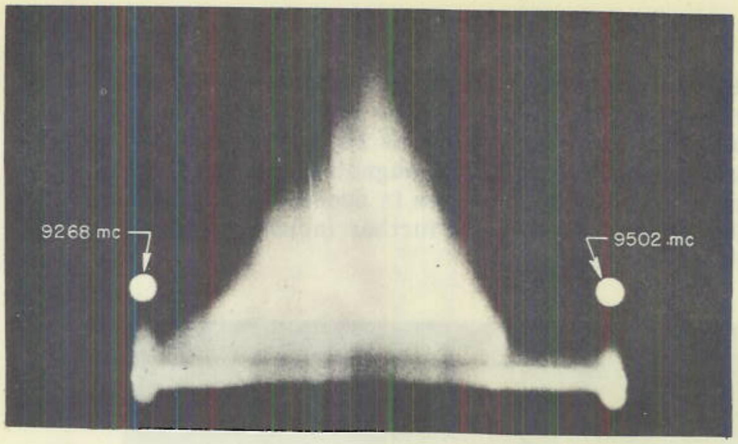


Figure 13 - R-F spectrum - 0.010 μsec

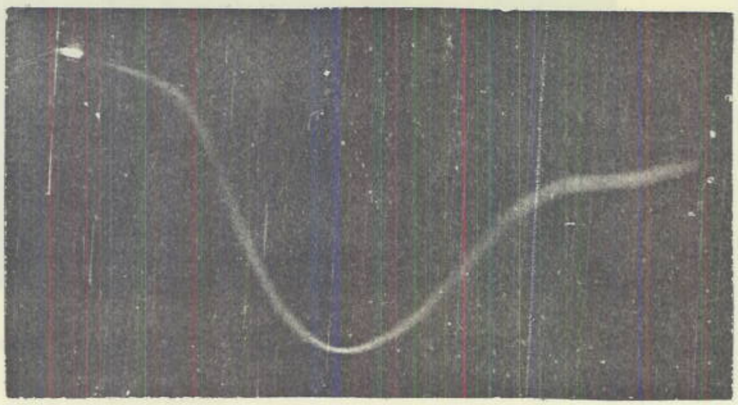


Figure 14 - Voltage pulse - 0.013 μsec - sweep length 0.05 μsec

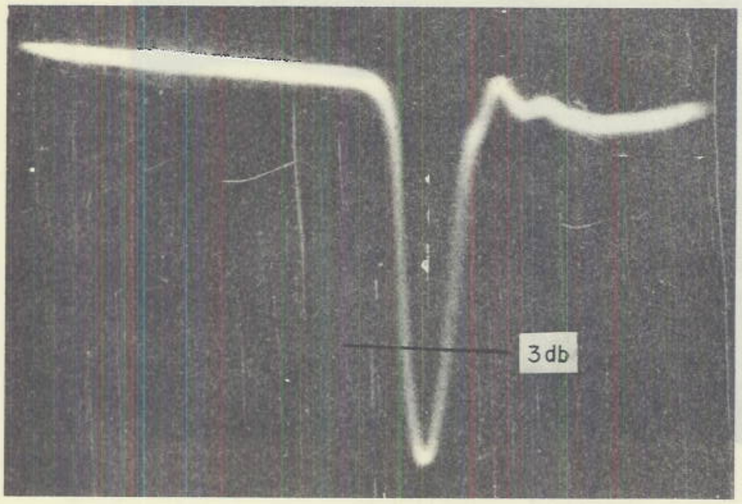


Figure 15 - Voltage pulse - 0.013 μsec - sweep length 0.13 μsec

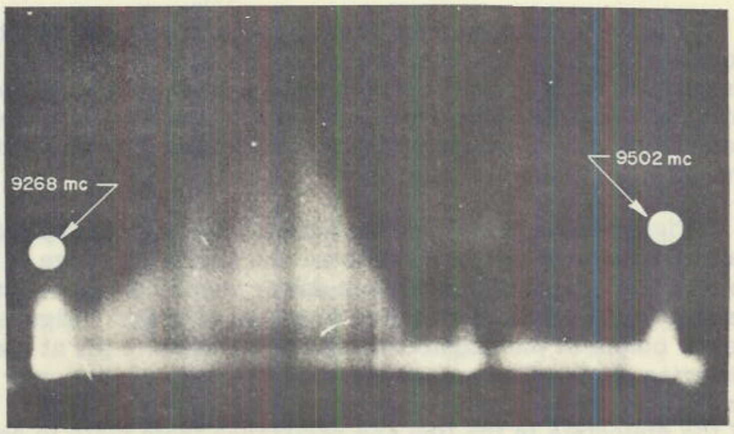


Figure 16 - R-F spectrum - 0.013 μsec

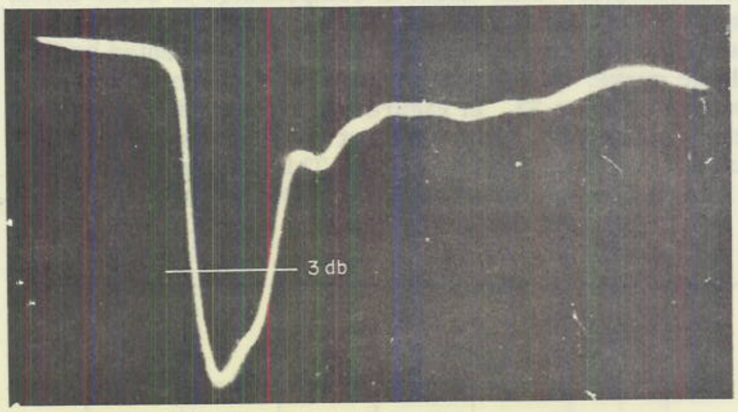


Figure 17 - Voltage pulse - 0.038 μsec - sweep length 0.13 μsec

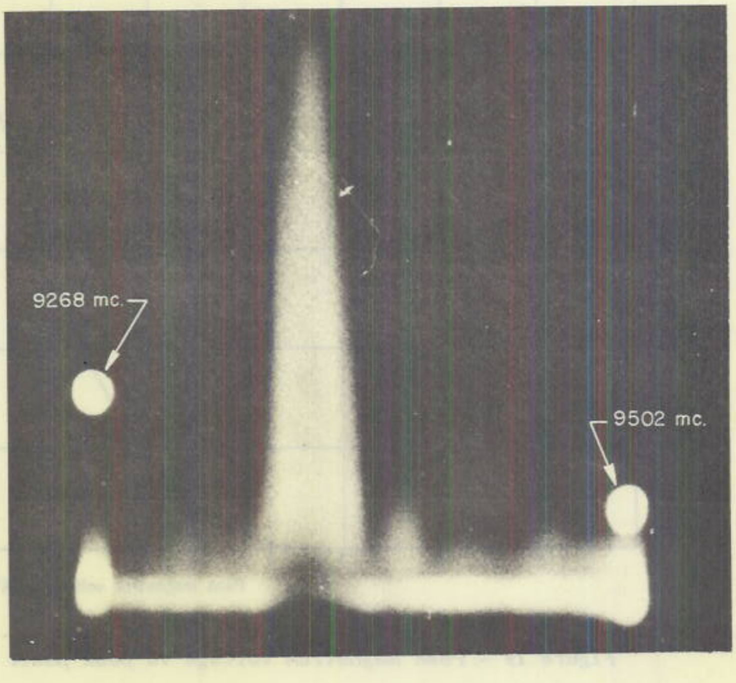


Figure 18 - R-F spectrum - 0.038 μsec

The performance of the final modulator with respect to prf power output, and the corresponding voltage conditions may be seen on Figures 19 through 24. The average magnetron output power with a constant input voltage to the modulator should vary directly with prf. Any deviation from normal is caused by such items as choke losses, leakage resistance, and plate dissipation in the 5C22. The above figures are a means of illustrating the effect of these parameters.

Figures 19 and 20 show the actual peak voltage applied to the magnetron for the condition of maximum power output over the operating range of prf. For the particular magnetron in this test, the maximum output power was 25 db above one milliwatt; any increase or decrease in peak voltage resulted in a loss of power. Figure 21 is a representation of the power output of the magnetron with a variation in prf at a constant input voltage to the charging diode. The output decreases rapidly at the lower prf because of the loss in charge on the line, caused by leakage resistance of the modulator in operation. This is composed of the dielectric in the line and resistance from plate to cathode of the 5C22, and was computed to be 17 megohms in the final modulator. This effect is compensated to some extent by the regulation of the power supply as shown in Figure 22. The effect of overshoot on the charging cycle caused by losses and stray capacity of the choke is represented by the deviation from the normal logarithmic curve. The corresponding average diode current for this voltage condition is presented in Figure 23. In Figure 24, the variation of maximum average power output is plotted against prf. Here the input voltage was varied with prf to give the maximum power output over the operating range. This was an attempt to compensate by manual means the loss in line charge through the resistive path to ground.

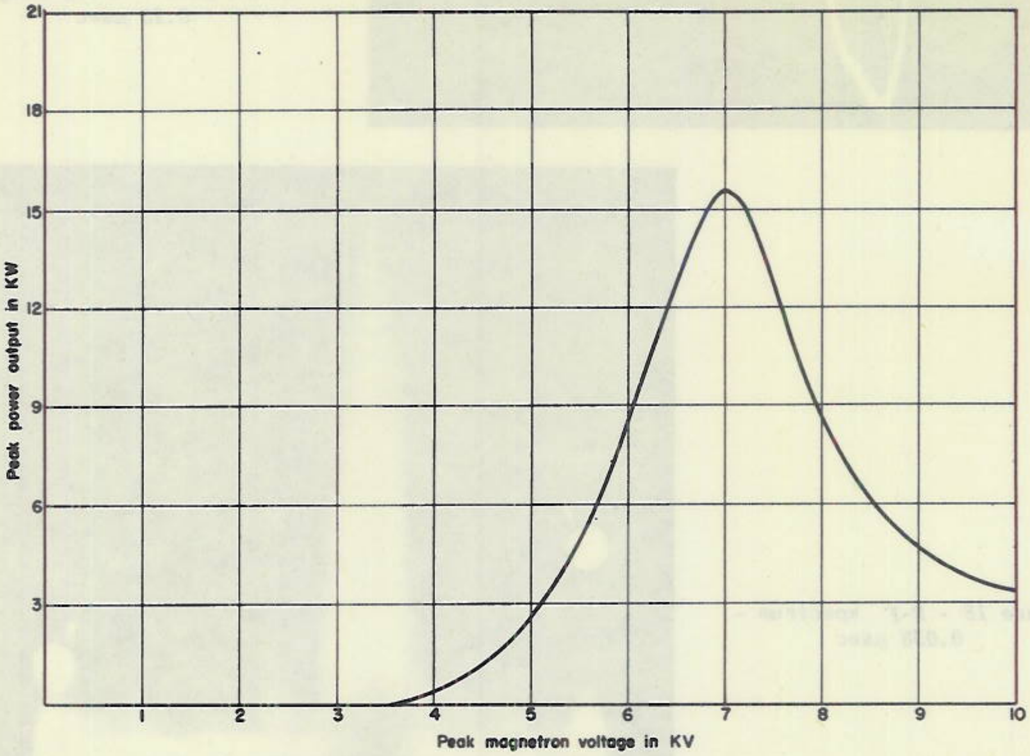


Figure 19 - Peak magnetron voltage vs peak power output for prf of 2000

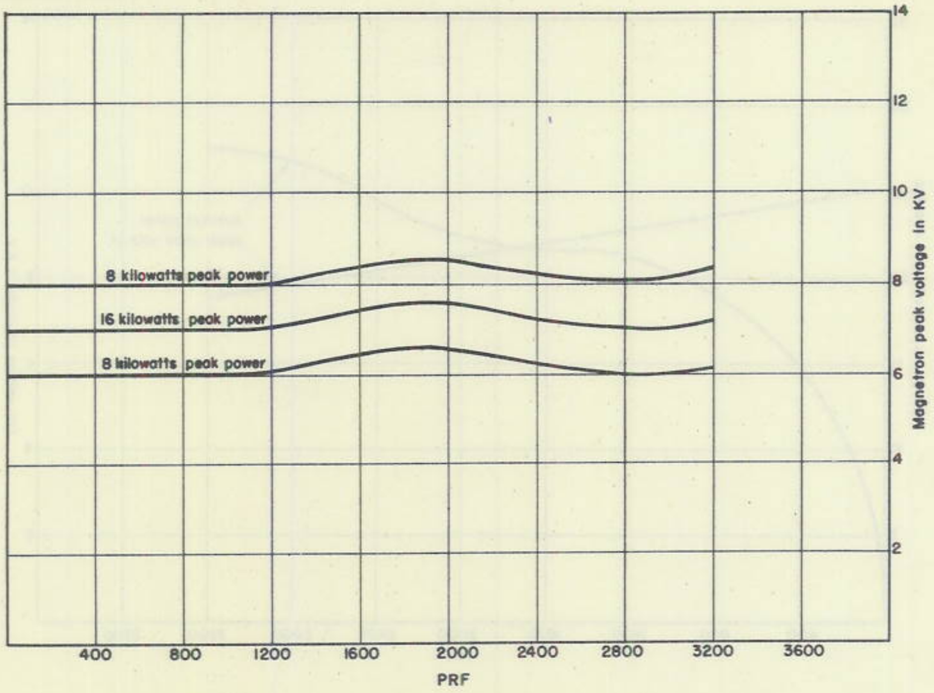


Figure 20 - Magnetron peak voltage vs prf

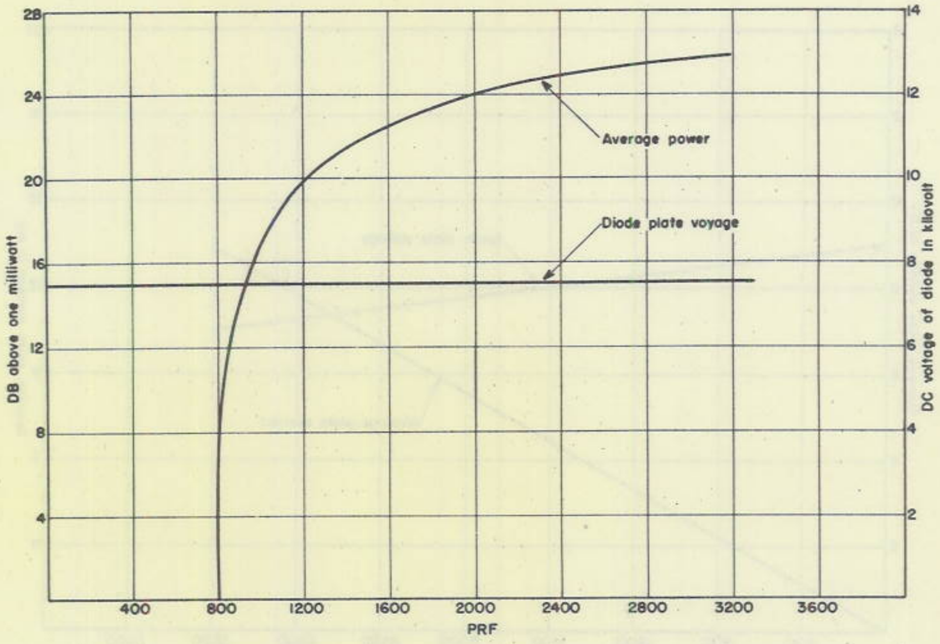


Figure 21 - Average power vs prf for a constant voltage at charging diode plate

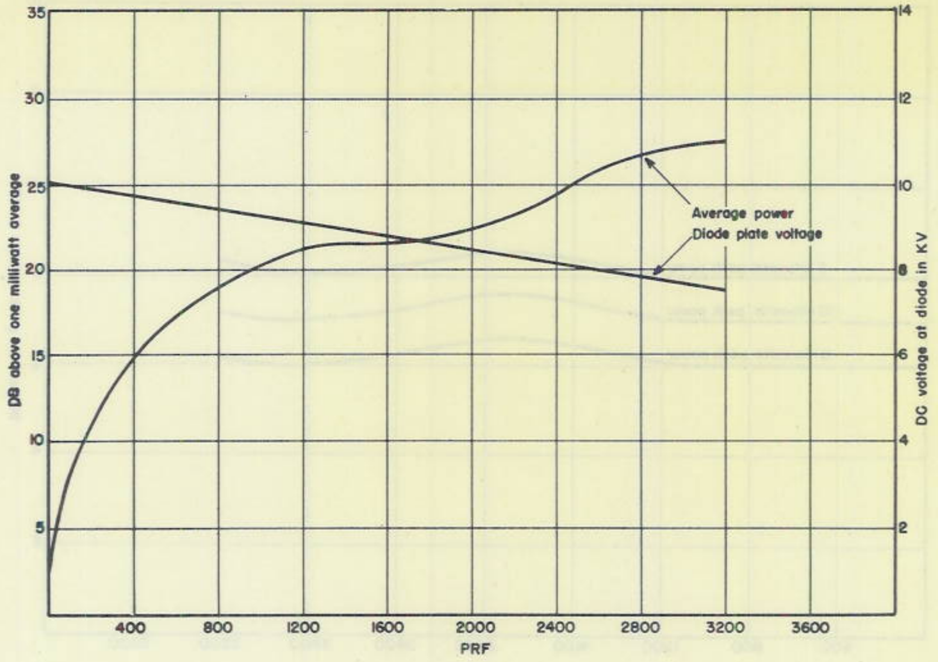


Figure 22 - Average power vs prf for diode voltage regulated by power supply regulation

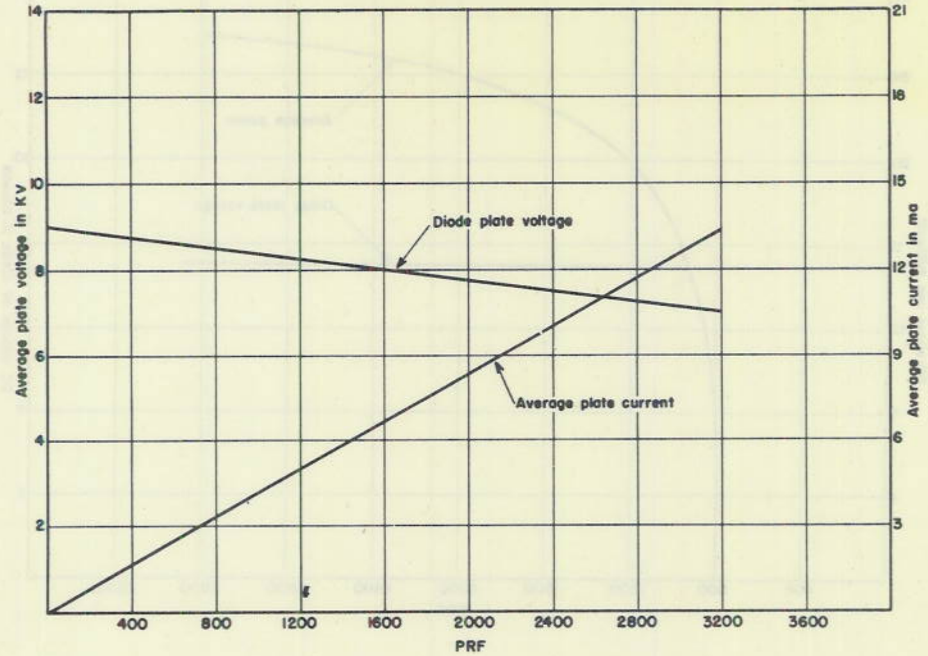


Figure 23 - Average diode current vs prf for diode voltage regulated by power supply regulation

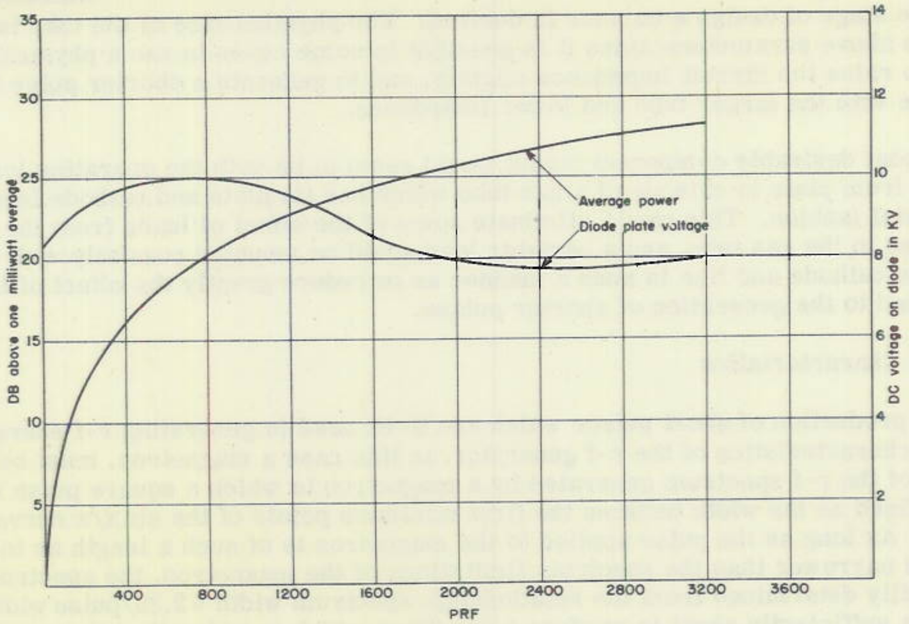


Figure 24 - Average power vs prf for voltage at diode adjusted for maximum power output

The peak power of the magnetron was found to be 15kw which appears to be the limit of power output of the 2J42 magnetron under conditions of short pulse operation without increasing the magnetic field in the magnetron. An increase of 3 db was obtained by increasing the magnetic field, but raising the over-all operating voltage in order to obtain this increase caused overheating of the 5C22 when operating at the maximum prf. To overcome this difficulty, it seems possible to fire two modulators alternately into a common load.

The jitter in the final modulator was approximately 0.001 microseconds with respect to the viewing scope when the filaments were on d.c. It seems that this jitter could be further reduced by a detailed study of firing characteristics with varying trigger impedances, trigger voltage shapes, etc. Operating the gas tube filaments on d.c. was the first step in reducing the jitter to such an extent that a study of the variation of many parameters with respect to jitter in firing of the tube is now possible.

DESIGN CRITERIA

Modulator Characteristics

To have the proper magnitude of impedance at which the circuit is to operate is essential for the generation of short pulses. This impedance is fixed by the minimum stray capacity of the circuit and the rise time expected of the pulse. Since pulse transformers of the required bandwidth are not available, the impedance in linear combination with the circuit current gives the voltage pulse available. The voltage and current requirements govern the choice of the type and size of gas tube to be used, thus introducing a physical size limitation to the circuit.

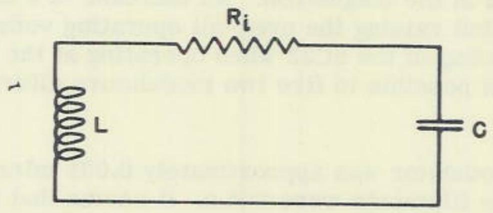
At this stage of design a balance is desired. The physical size of the tube is balanced against the above parameters since it is possible in some cases to use a physically smaller gas tube to raise the circuit impedance slightly, and to generate a shorter pulse than would be possible with the larger tube and lower impedance.

The most desirable component layout would seem to be with the operating load tied physically from plate to cathode of a gas tube which has its plate and cathode leads brought out in coaxial fashion. This would eliminate some of the effect of leads from the pulse-forming line to the gas tube, and a resistor load could be mounted coaxially with the plate between the cathode and line in such a manner as to reduce greatly the effect of lead lengths and thus lead to the generation of shorter pulses.

Magnetron Characteristics

In the production of short pulses which are to be used in generating r-f energy, the bandwidth characteristics of the r-f generator, in this case a magnetron, must be considered. The width of the r-f spectrum generated by a magnetron to which a square pulse is applied, is here defined as the width between the first minimum points of the $\sin x/x$ curve of the spectrum. As long as the pulse applied to the magnetron is of such a length as to produce a spectrum narrower than the spectrum limitations of the magnetron, the spectrum width can be readily determined from the relationship: spectrum width = 2.25/pulse width. When the pulse is sufficiently short to produce a spectrum which is wider than the capabilities of the magnetron, the spectrum of the magnetron output does not increase with a decrease in pulse length applied. This limitation in bandwidth can be computed approximately for a 2J42 as follows.

The magnetron can be approximated by the following circuit.



The unloaded (Q_u) can be found in tables for a 2J42 as 900, the C/L ratio as 0.019, and the internal resistance R_i as 0.008 ohms. The operating frequency is 9375 Mc. Since

$$Q_u = \frac{\omega L}{R_i}, \tag{1}$$

Q_u can also be written as

$$Q_u = \frac{1}{\omega C R_i}.$$

Therefore

$$900 = \frac{1}{\omega C R_i} . \qquad (2)$$

Multiplying (1) and (2)

$$(Q_u)^2 = \frac{\omega L}{R_i^2 \omega C} , \qquad (3)$$

and substituting C/L as 0.019

$$R_i = 0.008 \text{ ohms}$$

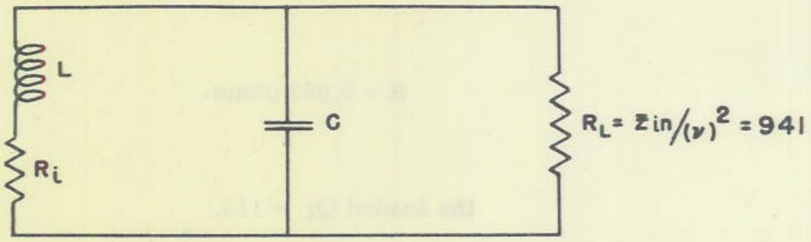
The waveguide can be approximated as a resistor calculated as follows

$$Z_{in.} = \frac{377 \sqrt{\mu / e}}{\left(1 - \frac{(fc)^2}{(f)}\right)^{\frac{1}{2}}}$$

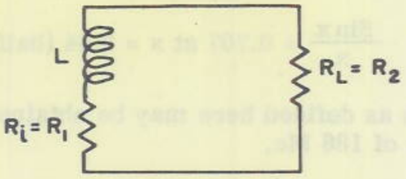
Since the magnetron frequency is 9375 Mc and the cutoff frequency of the waveguide is 6550 Mc,

$$Z_{in.} = 527 \text{ ohms.}$$

For preliminary calculations, let us assume a 75 percent coupling factor (ν) and couple this impedance directly across the magnetron. The circuit then becomes



Transferring R_1 into the following circuit for computing Q



and finding the equivalent resistance or real component gives

$$\frac{(R_1 + j\omega L)\,(R_2)}{R_1 + R_2 + j\omega L} = \frac{(R_1R_2 + jR_2\omega L)\,(R_1 + R_2 - j\omega L)}{(R_1 + R_2 + j\omega L)\,(R_1 + R_2 - j\omega L)}$$

The real component is

$$\frac{R_1^2 R_2 + R_2^2 R_1 + R_2(\omega L)^2}{(R_1 + R_2)^2 + \omega L}$$

Substituting from equation (1),

$$\frac{\omega L}{R_1} = 900$$

where

$$\omega L = 7.2$$

$$R_2 = 941$$

$$R_1 = 0.008$$

The real component is 0.063 ohms, since

$$Q_L = \frac{\omega L}{R}$$

where

$$R = 0.063 \text{ ohms}.$$

Then

the loaded $Q_L = 115$.

The bandwidth, is

$$\frac{f}{Q_L} = 82 \text{ Mc to the half power points.}$$

Since

$$\frac{\sin x}{x} = 0.707 \text{ at } x = 0.44 \text{ (half power point)},$$

an equivalent spectrum width as defined here may be obtained by dividing 82 Mc by 0.44 giving an expected bandwidth of 186 Mc.

The following magnetron bandwidth experiments show the limit of pulse width that can be applied to the magnetron.

Magnetron	C/L Ratio	Unloaded Q_u	Loaded Q_u	Spectrum Width Estimated to Minimum in Mc	Experimental Spectrum Widths in Mc	Pulse Width Required μsec
2J41	0.033	5000	1250	11	14 ± 2	0.11
2J42	0.019	900	115	186	163 ± 10	.013
*725A	0.107	650	238	98	67	.03

**Josephson, V., "Short Pulse Techniques for High Definition Radar Systems," MIT Radiation Laboratory report 912, 13 March 1946, (Unclassified)*

Any decrease in pulse width applied to the magnetron results in no increase in spectrum width.

ACKNOWLEDGMENT

The author is indebted to Mr. I. W. Fuller and Mr. N. L. Davis for their part in the electrical development, and to Mr. S. J. Weller and Mr. J. R. Conlon, who were responsible for a very considerable part of the construction work.

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