A STUDY OF THE KLYSTRON OSCILLATOR

WITH DATA ON

THE 2K28 KLYSTRON OSCILLATOR

A STUDY OF THE KLYSTRON OSCILLATOR
WITH DATA ON
THE 2K28 KLYSTRON OSCILLATOR

By

JOE FARRAR CULVER

Bachelor of Arts

Northeastern State Teachers College

Tahlequah, Oklahoma

1941

Submitted to the Department of Physics

Oklahoma Agricultural and Mechanical College

In Partial Fulfillment of the Requirements

For the Degree of

MASTER OF SCIENCE

1949

APPROVED BY:

H E Harrington
Chairman, Thesis Committee

A. V. Pershing.
Member of the Thesis Committee

Sherman W Eager.
Head of the Department

D.C. McIntosh
Dean of the Graduate School

PREFACE

The purpose of this thesis is to study the reflex klystron oscillator, and make tests to determine the characteristics of the 2K28 klystron tube acting as an oscillator in the region of 3000 megacycles/second.

The principle of the klystron oscillator will be given, the particular equipment used in this work will be described, and testing procedure and conclusions discussed.

I wish to acknowledge the assistance given me by Dr. H. E. Harrington in this work.

J. F. C.

TABLE OF CONTENTS

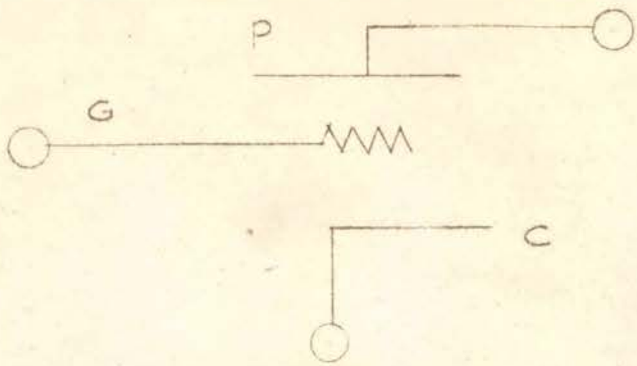
I. COMPARISON OF LOW VELOCITY MODULATED TUBES AND HIGH VELOCITY MODULATED TUBES.

The klystron tube differs from the usual amplifier tubes in that the signal is applied to the electron stream of the klystron after it has been given a high velocity, while in the usual amplifier the signal is applied to a slow moving electron stream which is then accelerated by plate or screen voltages. Both types of tubes may be made to oscillate if proper feedback conditions are provided.

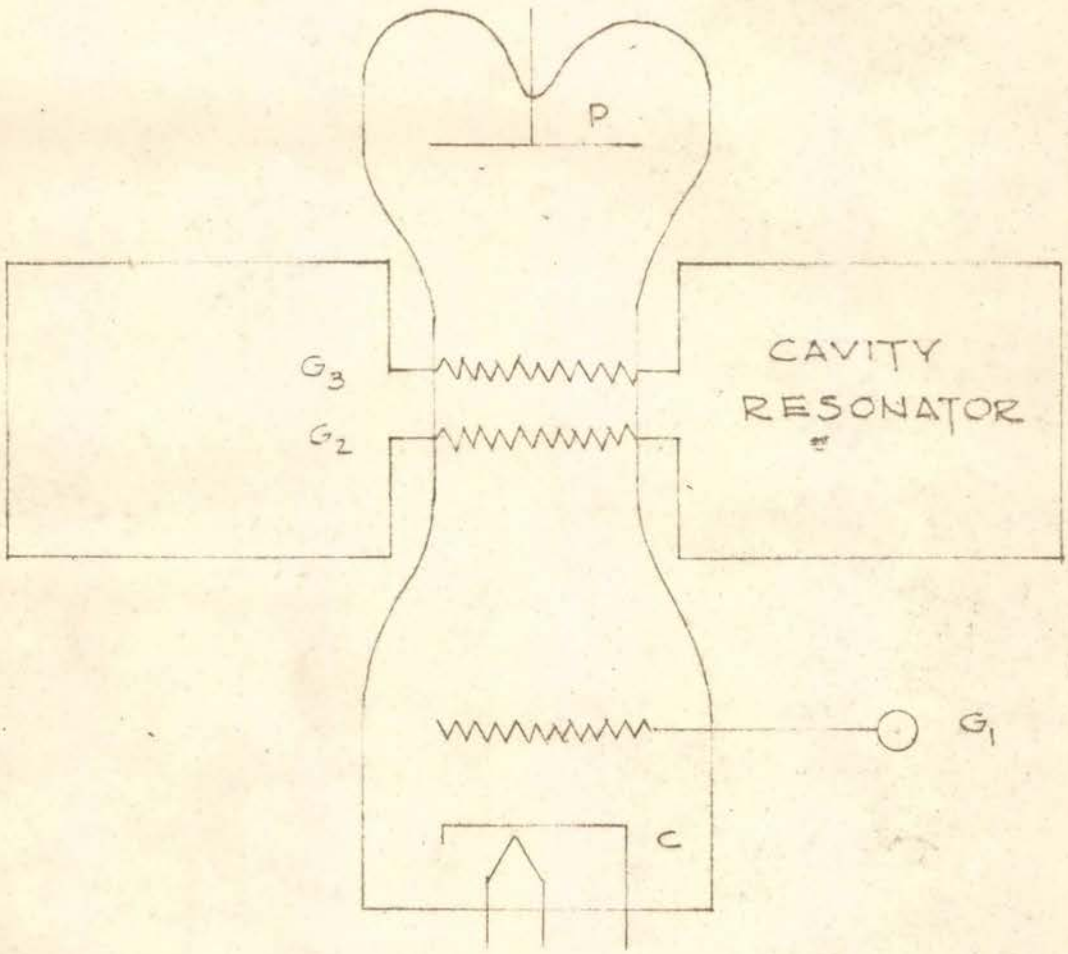
The low velocity type tube is limited to the frequencies which it may amplify, due to the phase change within the tube when the transit time of the electron stream is an appreciable part of a cycle. This transit time becomes important at higher frequencies, as there is a limit to the closeness at which the elements may be spaced.

The high velocity klystron tube takes advantage of this transit time and uses it to "bunch" the electron stream by velocity modulation, thus providing amplification. The spacings of the elements of the tube may be much greater in a klystron than for a low velocity modulated tube.

In figure 1 (a) is a low velocity tube in which the signal is injected on G with respect to the cathode. There is a low D-C electric field gradient existing in the space between C and G, therefore there is little acceleration of



(a) LOW VELOCITY MODULATED TUBE
TRIODE TYPE



(b) HIGH VELOCITY MODULATED TUBE
REFLEX KLYSTRON TYPE

FIGURE 1

the electron stream between these two elements, and the signal voltage acts on a slowly moving stream of electrons. Between G and P there is a high D-C electric field gradient and the electron stream is greatly accelerated, but only after the signal has modulated the electron stream. The spacing between C and G must not be more than $\frac{1}{2}$ wavelength or detrimental phase effects will be introduced during transit time. Since the velocity is low between C and G, the spacing of these elements becomes a serious problem at ultra high frequencies.

In figure 1 (b) is represented the construction of a high velocity tube. There is a large D-C electric field gradient between C and G_1, and the electron stream passes G_1 with a high velocity. There is usually no difference in the D-C potentials of G_1, G_2, and G_3, and the electron stream is not accelerated further in these spaces due to D-C field gradients. The signal voltage is applied between G_2 and G_3, and produces an acceleration or deceleration of the electrons between these elements as G_3 is positive or negative respectively with respect to G_2. The spacing of G_2 and G_3 is of the order of $\frac{1}{2}$ wavelength, which, because of the higher velocity of the electron stream, is large compared to the spacing of the elements in a low velocity tube. The spacing of other elements in the high velocity tube is not critical since signal voltage is not applied to them. Beyond G_3 there may be different combinations of elements, but again the spacing is not critical.

Klystron tubes are popular at ultra high frequencies because they are mechanically easier to construct, due to the larger spacings between elements.

II. GENERAL INFORMATION ON KLYSTRON TUBES

Klystron oscillator tubes fall under various classifications,[1] as follows:

1) Two cavity oscillators
2) Reflex klystron oscillators
3) Secondary-emission reflex oscillators
4) Oscillator-buffer klystrons
5) Floating-drift-tube klystron oscillators
6) Heil tube oscillators

This work shall be concerned with the reflex klystron oscillator, to which group the 2K28 tube belongs. The 2K28 was previously known as the 707B.

One of the advantages of the reflex klystron oscillator is its simplicity of tuning and elimination of tracking problems. Another is the electronic tuning characteristics, which are wide enough to be suitable for frequency modulation. This latter characteristic is also a drawback as it requires very good voltage regulation if the tube is to be operated at a fixed frequency. Frequency changes of the order of 30 megacycles/second (to the half power points) may be obtained by repeller voltage variations of the order of 30 volts.[2]

---

[1] Hamilton, Knipp, and Kuper, Klystrons and Microwave Triodes, pp. 26-30.

[2] Ibid., p. 27.

The efficiency of the reflex klystron oscillator at 3000 megacycles/second is of the order of 2% to 2.5%, with a power output of the order of 150 milliwatts.[3] Because of this lower power output of the reflex klystrons that were developed, their greatest application was in local oscillator operation.

In view of this limited use of reflex klystrons it is interesting to note that the two resonator klystron oscillator was developed for high power transmitter operation with higher efficiencies than the reflex klystron oscillators. Their power outputs for pulse modulated and cw operation were of the order of tens of kilowatts peak power at 20% efficiency, and 15 watts at 8% efficiency, respectively.[4]

The operating characteristics of the 2K28 klystron tube, manufactured by Raytheon, are as follows:[5]

Frequency range------------1200 to 3750 mc/sec.

Beam voltage--------------250 volts

Beam current--------------25 milliamps

Repeller voltage-----------110 to 230 volts

Power output--------------70 to 110 milliwatts

Electronic tuning range---21 to 22 mc/sec.

Electronic tuning rate----.85 to .60 mc/sec./reflector volt

---

[3] Ibid., loc. cit.

[4] Ibid., p. 26.

[5] Montgomery, Carol G., Technique of Microwave Measurements, p. 35.

III. THEORY OF THE REFLEX KLYSTRON OSCILLATOR

A. General Theory

The reflex klystron oscillator, see figure 1 (b), is a high velocity tube which uses the principles of velocity modulation and bunching to produce high frequency power. It has the advantage of using a single resonator cavity. A stream of electrons are accelerated by approximately 250 volts D-C on G_1. This stream, in passing through the resonator gap (between G_2 and G_3), is velocity modulated. The electrons are turned back in the space between G_3 and P, and re-enter the resonator gap. The time spent between the center of the gap field and the repeller plate is called the transit time. Bunching of the electrons takes place during this transit time, due to the velocity modulation. The bunching rate is not changed by P, but depends only on the velocity modulation given by G_2 and G_3. If these bunches return to the resonator in sufficiently strong bunches, and at the proper time to be decelerated at a maximum, energy will be given up to the gap field. This gap is part of the resonator circuit; and this transfer of energy will produce oscillations, providing that successive groups return to the gap at the proper intervals. The frequency of the oscillations will be near the resonant frequency of the resonator, but will vary from this frequency with changes in accelerator and repeller voltages. These two voltages determine the time taken to return the electron bunches to the resonator gap. If the transit time is too far from the optimum value, oscillations will cease.

The condition of optimum transit time is determined by the fact that the center of the bunches in the returning stream should pass the midpoint of the gap when the gap field provides the greatest retarding effect (deceleration). Under this condition, the greatest number of electrons will lose the greatest amount of energy, and the maximum energy is returned to the resonator circuit. The maximum retardation on returning center-of-the-bunch electrons occurs at 3/4, 1 3/4, 2 3/4, ----n 3/4 of a cycle after they have initially passed the center of the gap field. The possible modes of oscillation occur at transit times near 3/4, 1 3/4, ----n 3/4 of a cycle.[6] These different modes are produced by changing repeller voltage.

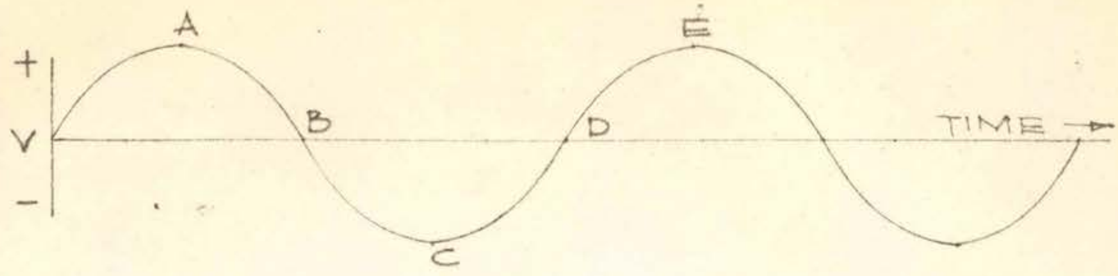
B. Velocity Modulation

Assume the klystron already in oscillation, the initial excitation necessary to start oscillation being due to inherent tube noises which cause small variations in the tube current. The RF voltage appears between G_3 and G_2 and will be given as G_3 with respect to G_2.

Refer to figure 2. Electrons which are at the midpoint between G_3 and G_2 at the time the RF voltage is at A,

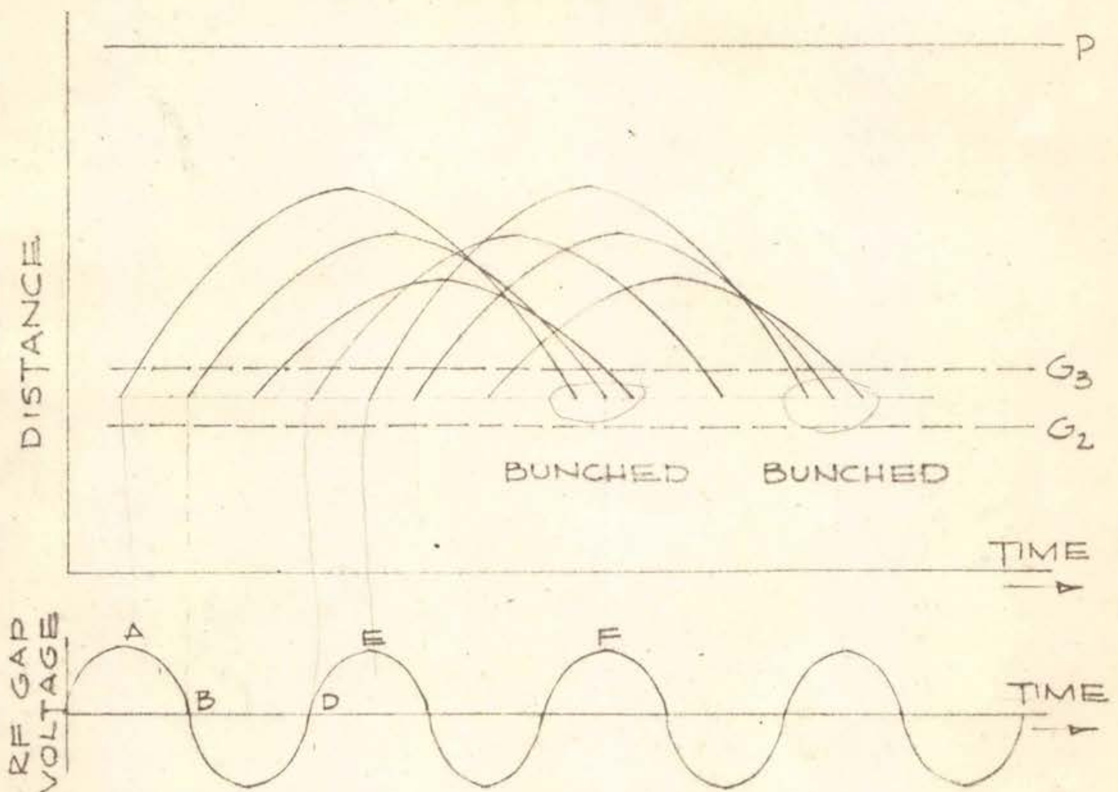
---

[6] Hamilton, Knipp, and Kuper, op. cit., p. 312.



RF VOLTAGE ON G_3 WITH RESPECT TO G_2

FIGURE 2



BUNCHING IN REFLEX KLYSTRON

FIGURE 3

will receive a maximum acceleration while passing through the gap, and leave G_3 with a maximum velocity.

Electrons which appear at the midpoint of the gap at time B will receive acceleration and then deceleration while passing through the gap, the average being zero. These electrons will leave the gap with the same velocity with which they entered.

Electrons which are at the midpoint at time C will receive a maximum deceleration through the gap and will leave with a minimum velocity.

Electrons which are at the midpoint at time D will receive deceleration and then acceleration while passing through the gap, the average being zero. These electrons will leave the gap with the same velocity with which they entered.

The electrons mentioned will be referred to as the A, B, C, and D electrons. The different electrons which enter the gap with the same velocity and leave with different velocities are said to be velocity modulated.

It can be seen that there will be an amount of energy given by the gap to the electrons which are accelerated, and an equal amount of energy given back to the gap by the electrons which are decelerated. The total energy transfer during velocity modulation of these electrons is seen to be zero.

C. Bunching

The action of the electrons in the gap over a period of one cycle has been studied. Now follow their action in the space between G_3 and the repeller plate P. Refer to figure 3. P is normally 400 to 450 volts D-C negative with respect to G_3, for the strongest mode of oscillation. Although this voltage is strong enough to decelerate the electron stream to zero velocity, and then accelerate them in a reverse direction, the action is constant and no change is produced in this space by this D-C voltage other than reversal in direction. The bunching action is not affected. The fastest electrons travel the greatest distance before reversal, and the slowest electrons travel the least distance before reversal. In figure 3 is shown how the faster and slower electrons group together. It can be seen that the bunching is not sharply defined. The center of the bunches is the B electrons. Electrons which form the center of minimum bunching (debunching) are the D electrons.

If the electrons return, so that when the signal voltages are decelerating the electrons in the gap, a maximum number of electrons are there (bunched), a large energy will be given to the gap circuit. If, when the signal voltages give an acceleration to the returning electrons, a minimum number are there (debunched), a minimum energy will be given by the gap circuit to the electron stream. If the above is accomplished, a larger energy will be received by the gap circuit then it returns to the electron stream. On the average the gap circuit is receiving energy. If this energy is sufficient for the losses and the load, oscillations may be sustained.

From the above it is seen that maximum average energy is returned to the gap circuit when the greatest bunching passes through the gap for the time of greatest average deceleration. The maximum density bunch must be at the center of the gap when G_3 is a maximum positive.

This can be accomplished by adjusting the repeller and accelerator (beam) voltages. The frequency of oscillation will be that with which the bunches return to the gap, providing this is not too far removed from the natural frequency of the resonant circuit.

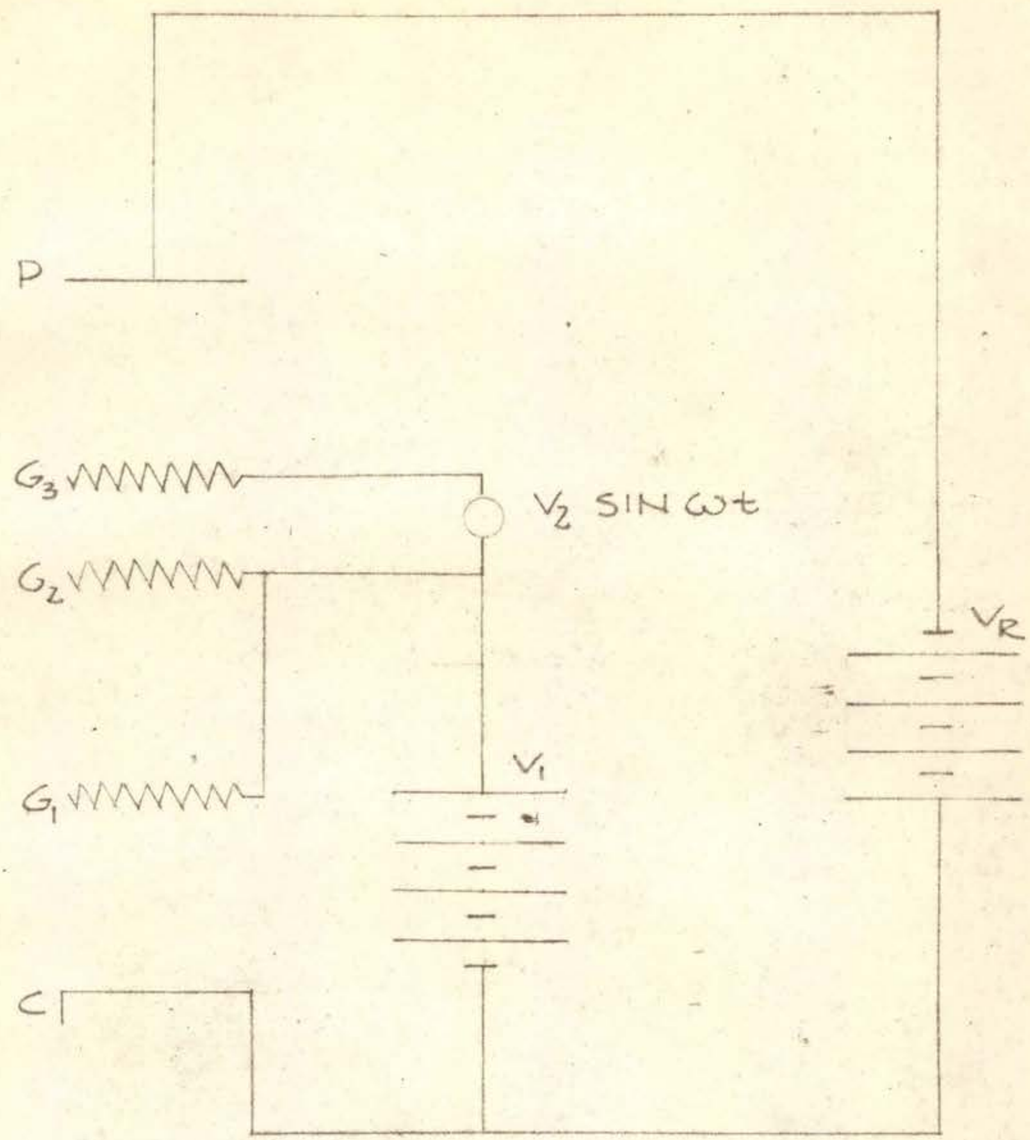
D. Mathematical Analysis[7,8]

An expression relating the time of departure of electrons from the resonator grids and the return arrival time will be derived for the reflex klystron oscillator. This will establish a relationship between the various electrode potentials which must be satisfied if oscillating conditions are obtained.

---

[7] Bronwell and Beam, Theory and Application of Microwaves, pp. 86-106.

[8] Ginzton and Harrison, "Reflex Klystron Oscillators," Proceedings I.R.E., XXXIV (March, 1940), p. 97.



REFLEX KLYSTRON OSCILLATOR POTENTIALS

FIGURE 4

Figure 4 shows the potentials of the various electrodes of the reflex klystron while oscillating. The cathode is taken as the zero potential electrode and an A-C potential is assumed to exist between the cavity grids. The potentials of G_2 and G_3 are assumed to be V_1 and $V_1+V_2\sin\omega t$ respectively, while that of the repeller plate p is a negative potential V_R. The potential of G_1 is the same as the potential of G_2.

The electrons enter G_2 with a velocity

$$v_1 = (2V_1e/m)^{\frac{1}{2}} \tag{1}$$

The electrons leave G_3 with a velocity

$$v_2 = v_1\left[1 + (V_2/V_1)\sin\omega t_1\right]^{\frac{1}{2}} \tag{2}$$

The potential difference between G_3 and the repeller plate is $V_R - (V_1+V_2\sin\omega t)$. Assume that $V_2\sin\omega t$ is small compared to the other terms, and write the potential difference as $V_R - V_1$. Assume a uniform field between G_3 and the repeller plate, the electric field intensity will then be $E = -(V_R - V_1)/s$, where s is the distance between G_3 and P.

The force experienced by the electron in the repelling region is $-eE= e(V_R - V_1)/s$. Equating force to mass times acceleration, we obtain the equation of electronic acceleration.

$$a = e(V_R - V_1)/ms \tag{3}$$

The time T spent by an electron in the repelling region is given by

$$T = \frac{2v_2}{a} = \frac{2msv_1\left[1 + (V_2/V_1)\sin\omega t_1\right]^{\frac{1}{2}}}{e(V_R - V_1)} \qquad (4)$$

The time T_1 spent by a center-of-the-bunch-electron, which is not accelerated by the gap field, in the repelling region is given by

$$T_1 = \frac{2v_1}{a} = \frac{2msv_1}{e(V_R - V_1)} \qquad (5)$$

Returning electrons arrive at time t_2, having entered the repeller field at time t_1. Hence

$$t_2 = t_1 + T \qquad (6)$$

Expanding the bracketed term of equation 4, keeping the first two terms, substituting equation 5 into equation 4, and placing the resultant value of T into equation 6, we obtain

$$t_2 = t_1 + T_1\left[1 + (V_2/2V_1)\sin\omega t_1\right] \qquad (7)$$

Multiply through by   to obtain the phase angle, and set the center-of-the-bunch-electron transit angle $T_1 =$.

$$\omega t_2 = \omega t_1 + \alpha\left[1 + (V_2/2V_1)\sin\omega t_1\right] \qquad (8)$$

The round trip transit time has been previously discussed in this paper and found to be 3/4, 1 3/4, ----n 3/4 of a cycle. The corresponding round trip transit angle would be $2\pi n - \pi/2$, where n is an integer. The relationship between accelerating voltage and repeller voltage is found by inserting $\alpha = 2\pi n - \pi/2$, and v_1 from equation 1, into equation 5 multiplied by ω.

$$\frac{V_1}{(V_R - V_1)^2} = \frac{e(2\pi n - \pi/2)^2}{8\omega^2 s^2 m} \tag{9}$$

If V_R is the variable, the smaller values of n correspond to higher values of V_R.

The ratio of V_2/V_1 is given by

$$V_2/V_1 = 2x/\alpha \tag{10}$$

where x is the "bunching parameter" used later.

Return electrons give up energy $W = -eV_2 \sin \omega t_2$. The negative sign signifies energy return from the electron to the gap field. Using this sign convention, energy output and power output are positive quantities.

Substituting ωt_2 from equation 8

$$W = -eV_2 \sin \left\{\omega t_1 + \alpha \left[1 + (V_2/2V_1) \sin \omega t_1\right]\right\} \tag{11}$$

Averaging this equation for all electrons between $\omega t_1 = 0$ and $\omega t_1 = 2\pi$, the average energy returned to the resonator circuit, per electron, is obtained

$$W_{av} = \frac{-eV_2}{2\pi} \int_0^{2\pi} \sin \left\{\omega t_1 + \alpha \left[1 + (V_2/2V_1) \sin \omega t_1\right]\right\} \left\{d(\omega t_1)\right\} \tag{12}$$

Substituting the bunching parameter $x = \alpha V_2/2V_1$ and expanding, the integrand is obtained.

$$\sin(\omega t_1 + \alpha + x\sin\omega t_1)$$
$$= \sin(\omega t_1 + \alpha)\cos(x\sin\omega t_1)$$
$$+ \cos(\omega t_1 + \alpha)\sin(x\sin\omega t_1)$$

In standard treatment of Bessel's functions

$$\cos(x\sin\omega t_1) = J_o(x) + 2J_2(x)\cos 2\omega t_1 \text{-----------}$$
$$\sin(x\sin\omega t_1) = 2J_1(x)\sin\omega t_1 + 2J_3(x)\sin 3\omega t_1 \text{---}$$

When the first series is multiplied by $\sin(\omega t_1 + \alpha)$ and integrated between the limits of $\omega t_1 = 0$ and $\omega t_1 = 2\pi$ the integral has zero value since each term is of the form

$$\int_0^{2\pi} J_n(x)\sin(\omega t_1 + \alpha)\cos(n\omega t_1)\,d(\omega t_1)$$

where n is an even integer.

When the second series is multiplied by $\cos(\omega t_1 + \alpha)$ and integrated, each of the terms is of the form

$$\int_0^{2\pi} 2J_n(x)\cos(\omega t_1 + \alpha)\sin(n\omega t_1)\,d(\omega t_1)$$

All of the terms except that corresponding to $n = 1$ are zero. For $n = 1$

$$W_{av} = \frac{-eV_2}{2\pi}\int_0^{2\pi} 2J_1(x)\sin(\omega t_1)\cos(\omega t_1 + \alpha)\,d(\omega t_1)$$

$$= eV_2 J_1(x)\sin\alpha \qquad (13)$$

Multiplying W_{av}, the average energy per electron, by N, the number of electrons per second leaving the cathode

$$P = W_{av}N = NeV_2J_1(x)\sin\alpha$$

$$= I_1V_2J_1(x)\sin\alpha$$

where I_1 is the beam current.

Substituting $V_2 = 2xV_1/\alpha$

$$P = \frac{2I_1V_1xJ_1(x)\sin\alpha}{\alpha} \tag{14}$$

To find the power delivered to the load, P_L, consider the load as a resistance R_L parallel with the resonator. Resonator losses are in a resistance R_S.

$$P_L = P\left[\frac{R_S}{R_S+R_L}\right] = \left[\frac{2I_1V_1xJ_1(x)\sin\alpha}{\alpha}\right]\left[\frac{R_S}{R_S+R_L}\right] \tag{15}$$

The efficiency is given by

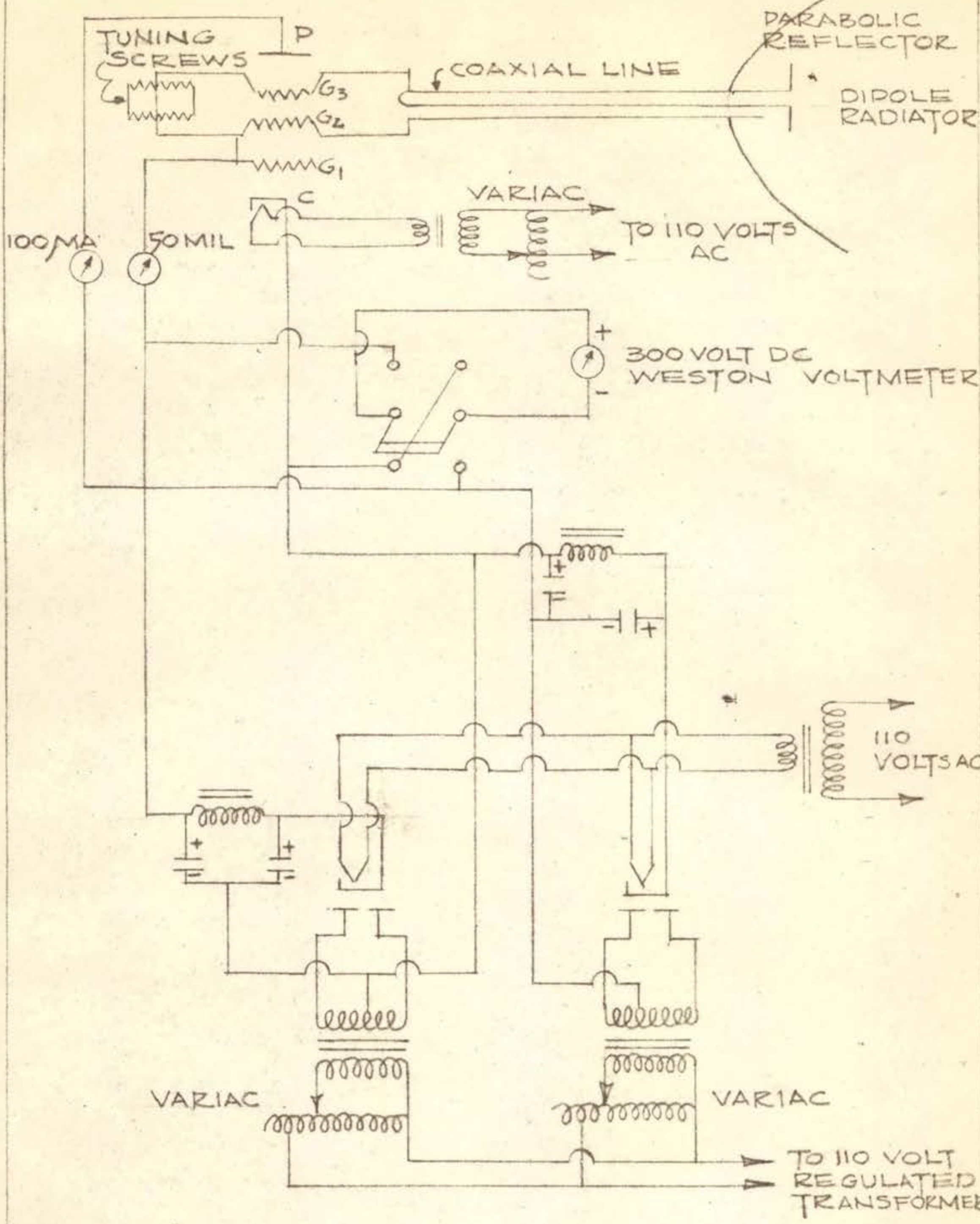
$$\eta = \frac{P_L}{P_{D-C}} = \left[\frac{xJ_1(x)\sin\alpha}{\alpha}\right]\left[\frac{R_S}{R_S+R_L}\right] \tag{16}$$

IV. POWER SUPPLY

It is essential in the operation of the reflex klystron oscillator at a fixed frequency that the power supply be regulated to within a fraction of a volt, because of the change in frequency with change in repeller voltage. If the regulation is such that no fluctuations are observable in any of the measuring instruments, during any particular setting, there is sufficient regulation.

For this work two ordinary condenser input filter power supplies with a bleeder resistance were used; one for the repeller voltage and one for the beam accelerator voltage. Each of these supplies was coupled into a 110 volt A-C regulated transformer through a separate variac, which provided the necessary manual regulation. See figure 5 for the power supply circuit. In addition to the regulation these variacs are convenient to set the voltages to different combinations for oscillations.

In the taking of data a careful watch was kept on all indicators. Particularly close check was made on the frequency meter, as frequency variation with change in D-C voltage is the prime purpose of elaborate regulation. No fluctuations in any of the instruments were observed.



POWER SUPPLY AND KLYSTRON CIRCUIT

FIGURE 5

V. TEST EQUIPMENT

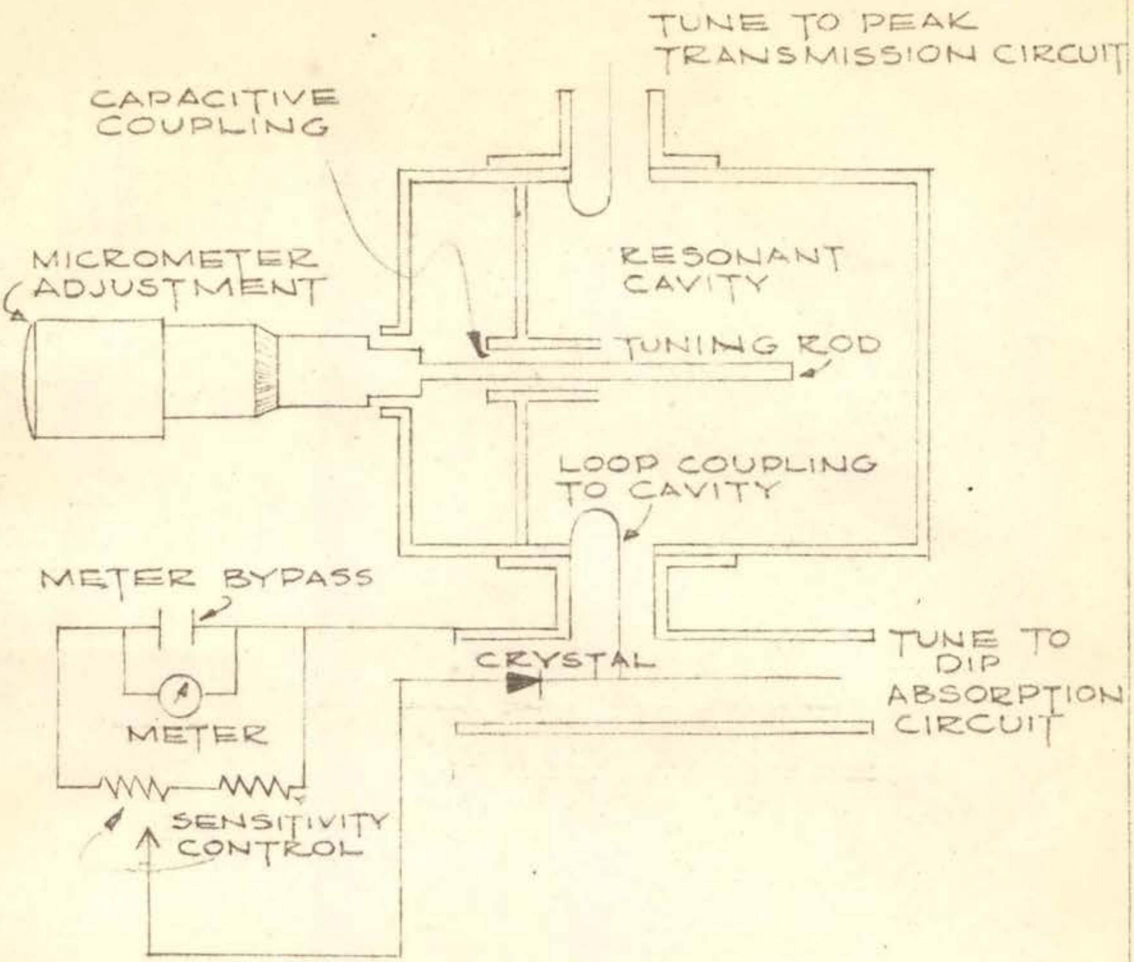
A. Voltmeters and Current Meters

A Weston D-C voltmeter model 45, 300 volt full scale, accurate to within ½%, and accepted by the Physics Department as a suitable standard, was used to measure repeller voltage and accelerator voltage. By a switching arrangement, see figure 5, the voltmeter was connected to read each voltage separately with respect to the cathode of the klystron tube.

A 50 milliampere full scale ammeter was placed in the accelerator circuit in such a manner as to measure the total beam current (G_1 plus G_2 plus G_3 current). A 100 microamp full scale meter was placed in the repeller circuit to note any unusual currents which might occur there. The repeller circuit normally draws only a few microamps of current, and this meter was placed in the circuit only as a check.

B. Frequency Meter

Frequency measurements were made with a Sperry Gyroscope Mark S22 Detector-wavemeter, whose accuracy is 1 part in 2000, placed in the radiation field. The absorption circuit was used. If the cavity is tuned to resonance, energy is absorbed by the cavity and the meter reading dips. The frequency is calibrated against the micrometer readings of the micrometer adjusted tuning probe of the wavemeter cavity. See figure 6 for the frequency meter diagram.



MARK 522
DETECTOR
WAVEMETER

FIGURE 6

C. Relative Power Meter

The meter used to measure relative power deserves some discussion, as these were the most difficult measurements to make. The relative power meter was the Sperry frequency meter used in making frequency measurements.

The Sperry meter was used as an absorption meter, with a dipole antenna coupled to the "tune to dip" connector. When the cavity is not resonant to the frequency being received, no energy is absorbed by the cavity. The energy in the coaxial line is rectified by the square law crystal detector, causing D-C to flow in the meter circuit. Thus the meter is a linear detector of power, if the cavity is not tuned to resonance.

VI. MEASUREMENTS AND CONCLUSIONS

A. General Information

Data on oscillators is usually taken in such a manner as to measure the maximum possibilities of the oscillator at any particular set of conditions. To make such power measurements, over the frequency range of the 2K28 klystron and cavity used in this work, would require variable matching networks and special couplings which are not available. Therefore, the power measurements made herein are not of the klystron alone, but rather of the oscillator and radiating antenna.

In practice the klystron works into a load which varies with frequency, and this load is designed to give nominal operation at some frequency of the klystron oscillator. No effort is made to match the load at all frequencies. If the frequency of the klystron oscillator is changed, by any of the methods of tuning, the load is changed, and a mismatch may exist.

Because of the above, it was thought that data on the klystron oscillator coupled to a fixed radiating antenna might be useful.

For all data, except one set to determine relative power output vs. frequency, a dipole antenna with a parabolic reflector was used. It was found that standing waves existed in front of this combination, but this was not harmful as long as the position of the nodes did not change.

All data was taken with the relative power meter placed so as to give a maximum indication, that is, the meter was placed at a node.

The position of the nodes did not vary as long as the frequency was not changed over a very large range. Frequency changes with change in beam voltage and repeller voltage were seen to be within this range. Thus relative power measurements, with change in beam and repeller voltages, are seen to be valid. See figures 8 and 10 respectively.

B. Calibration of the Sensitivity Control of the Relative Power Meter

The Sperry Mark S22 relative power meter was placed in the radiated field of the 2K28 oscillator, whose frequency was adjusted to 2910 megacycles/second, so that the meter read 50 with full sensitivity. Full sensitivity corresponds to a setting of 10 on the sensitivity control. Keeping all other conditions constant the sensitivity control was adjusted until the meter read 25 (50/2), and the position of the sensitivity control was recorded. This meant that when the sensitivity control was set to this position it would be necessary to multiply the meter reading by 2 to get the correct indication of the relative power of the field, to be related to power indications with full sensitivity.

Similarly, the sensitivity control was positioned to give meter readings of 50/3, 50/4, 50/5, 50/10, which meant

CALIBRATION OF THE SENSITIVITY CONTROL OF THE RELATIVE POWER METER

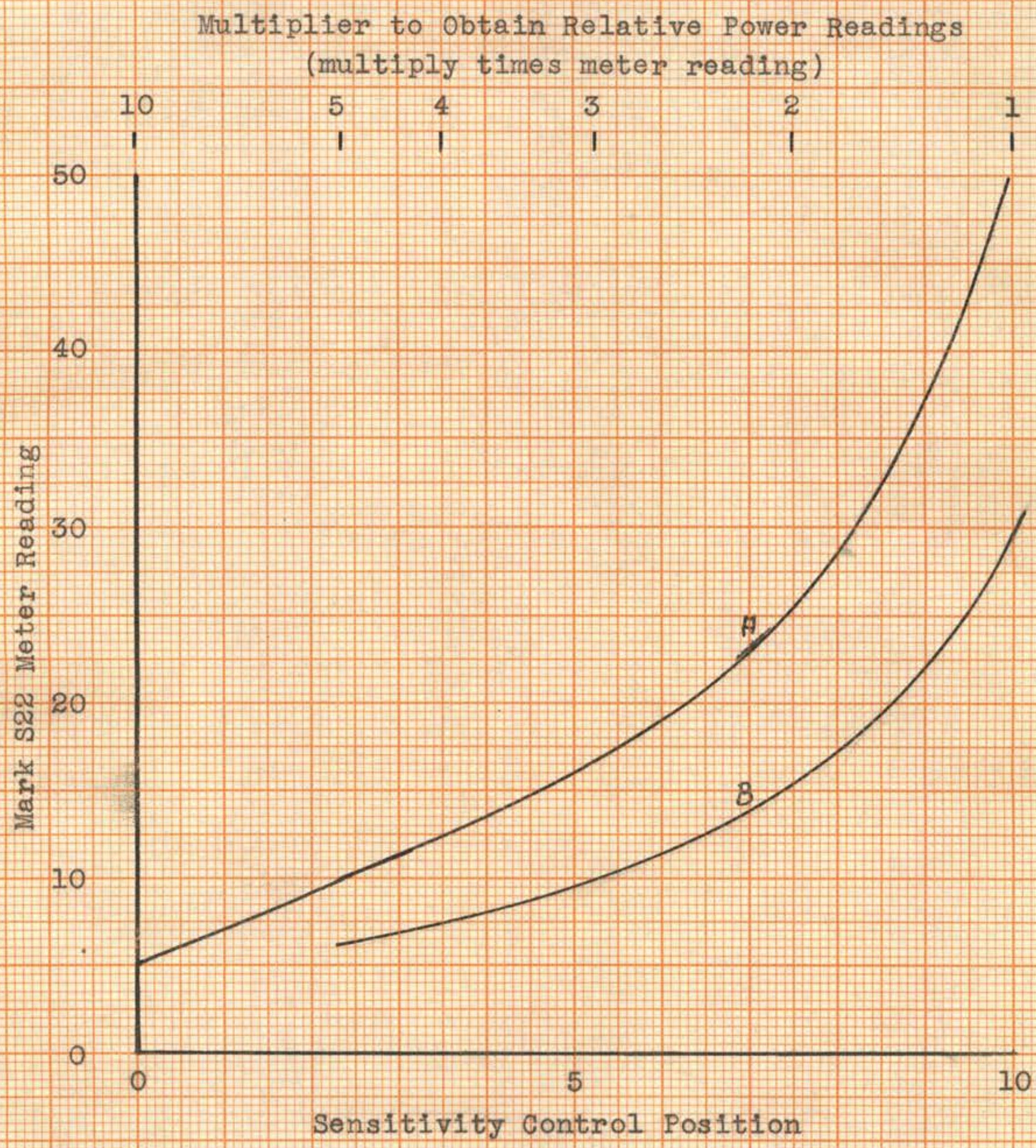


FIGURE 7

the meter reading must be multiplied by 3, 4, 5, and 10 respectively, to give the correct readings, when the sensitivity control was set to these respective positions.

The above was repeated at frequencies of 2988 and 3388 megacycles/second. The curves obtained at all three frequencies were identical and correspond to curve A in figure 7.

Curve B in figure 7 was obtained in the same manner as curve A, except the relative power meter was positioned to give a meter reading of 30 with full sensitivity. Positions requiring multipliers of 2, 3, 4, and 5, were obtained by recording the positions of the sensitivity control which gave meter readings of 30/2, 30/3, 30/4, 30/5, respectively.

This calibration was used in later measurements of relative power.

C. Beam Voltage Characteristics

At each particular setting of beam voltage (the D-C voltage on G_1, G_2, and G_3), starting at 260 volts and decreasing in steps of 10 volts until no signal output could be detected, the repeller voltage was adjusted to give a maximum output. This output corresponds to the peak of the highest repeller voltage mode of oscillation.

The relative power meter was placed in the radiated field, and its position remained constant. The relative power meter reading, the beam current, the frequency, and

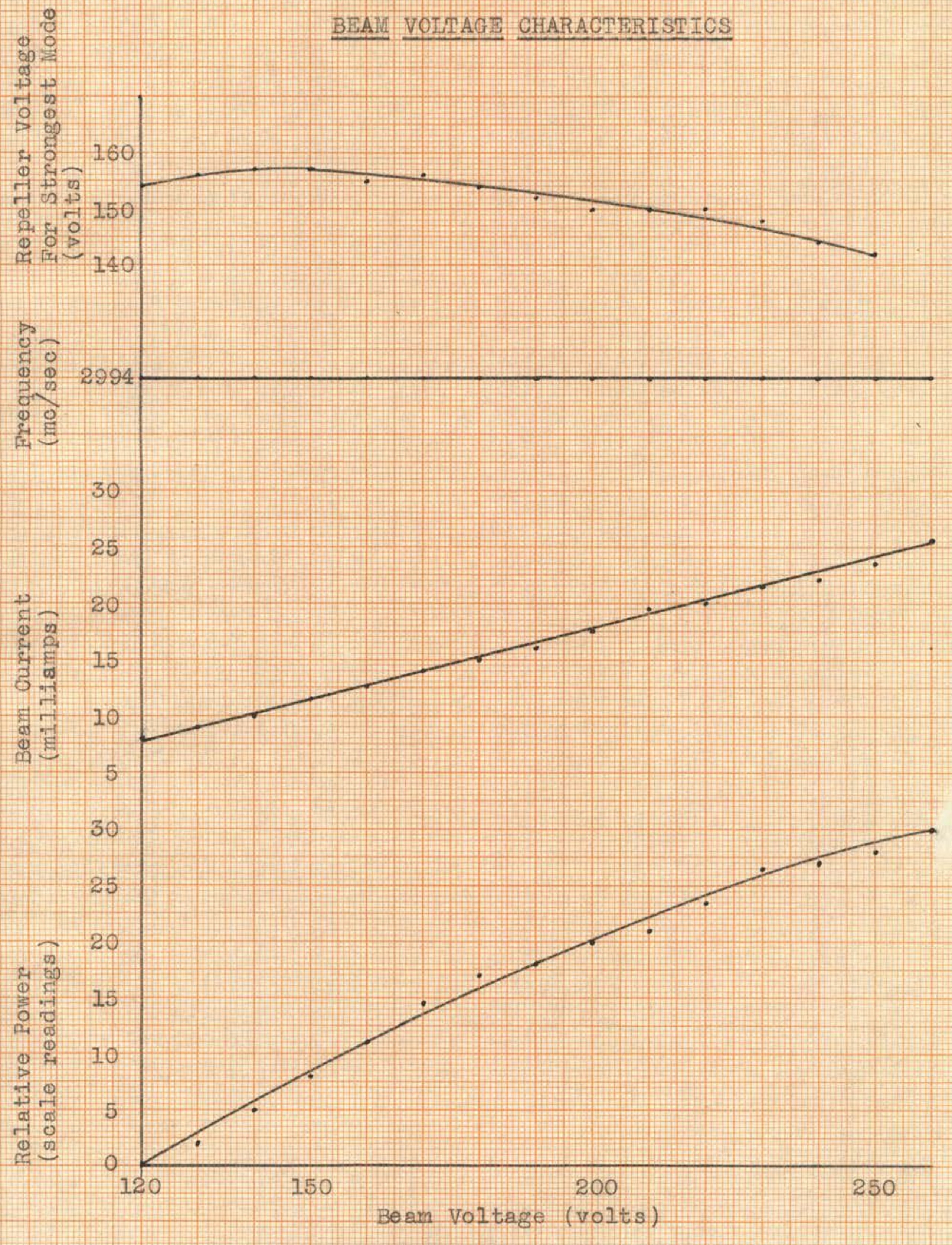

BEAM VOLTAGE CHARACTERISTICS
Repeller Voltage For Strongest Mode (volts)
160
150
140
Frequency (mc/sec)
2994
Beam Current (milliamps)
30
25
20
15
10
5
Relative Power (scale readings)
30
25
20
15
10
5
0
120
150
200
250
Beam Voltage (volts)

FIGURE 8

the repeller voltage were recorded for each setting of the beam voltage. The results are shown in figure 8.

The relative power and beam current curves are as to be expected, increasing steadily with increase in beam voltage.

The frequency curve shows no change in frequency with change in beam voltage, but it is to be remembered that both the beam voltage and repeller voltage were changed, which if properly adjusted would have time characteristics corresponding to the resonant frequency of the cavity. This curve therefore also appears to be as should be expected.

The repeller voltage vs. beam voltage curve shows an increase in repeller voltage as the beam voltage goes from 120 volts to 150 volts, and a decrease in repeller voltage as the beam voltage increases from 150 volts to 250 volts. It must be remembered that repeller voltage is negative with respect to the cathode, and beam voltage is positive with respect to the cathode.

It will be necessary to use specific numbers to show that this curve is that which should be expected.

The equation relating repeller voltage and beam voltage is $V_1/(V_R - V_1)^2 = (2\pi n - \pi/2)^2 e/8\omega^2 s^2 m$, where n is the number of the mode of oscillation.

Since this data was taken with a constant mode, and the frequency did not vary, the right hand side of the above equation is a constant. Evaluating this constant at the values of V_R and V_1 at the start of the experiment,

$$K = 250/(-142-250)^2 = .00162$$

Using this constant and new values of V_1, solve for expected values of V_R. Thus

$$V_R = \pm(V_1/.00162)^{\frac{1}{2}} + V_1$$

V_1 is always positive, and V_R is always negative, hence the negative value of $(V_1/.00162)^{\frac{1}{2}}$ must be used.

Let V_1 be 200, 175, 150, and 120 volts. Then

$$V_R = -(200/.00162)^{\frac{1}{2}} + 200 = 151.3 \text{ (volts)}$$

$$V_R = -(175/.00162)^{\frac{1}{2}} + 175 = 153.6 \text{ (volts)}$$

$$V_R = -(150/.00162)^{\frac{1}{2}} + 150 = 154.3 \text{ (volts)}$$

$$V_R = -(120/.00162)^{\frac{1}{2}} + 120 = 153.4 \text{ (volts)}$$

These values give the same general curve as was obtained from the data, repeller voltage decreasing on both sides of beam voltage equal 150 volts.

D. <u>Modes of Oscillation</u>

In figure 9 is shown the various modes of oscillation. This figure illustrates the fact that at any particular beam voltage there are different repeller voltages which will produce oscillation.

These repeller voltages are the ones which control the bunching time. When the voltage is adjusted so that the bunching time is 3/4, 1 3/4, etc., of a cycle, then oscillations will occur. Mode number 1, in figure 8,

MODES OF OSCILLATION

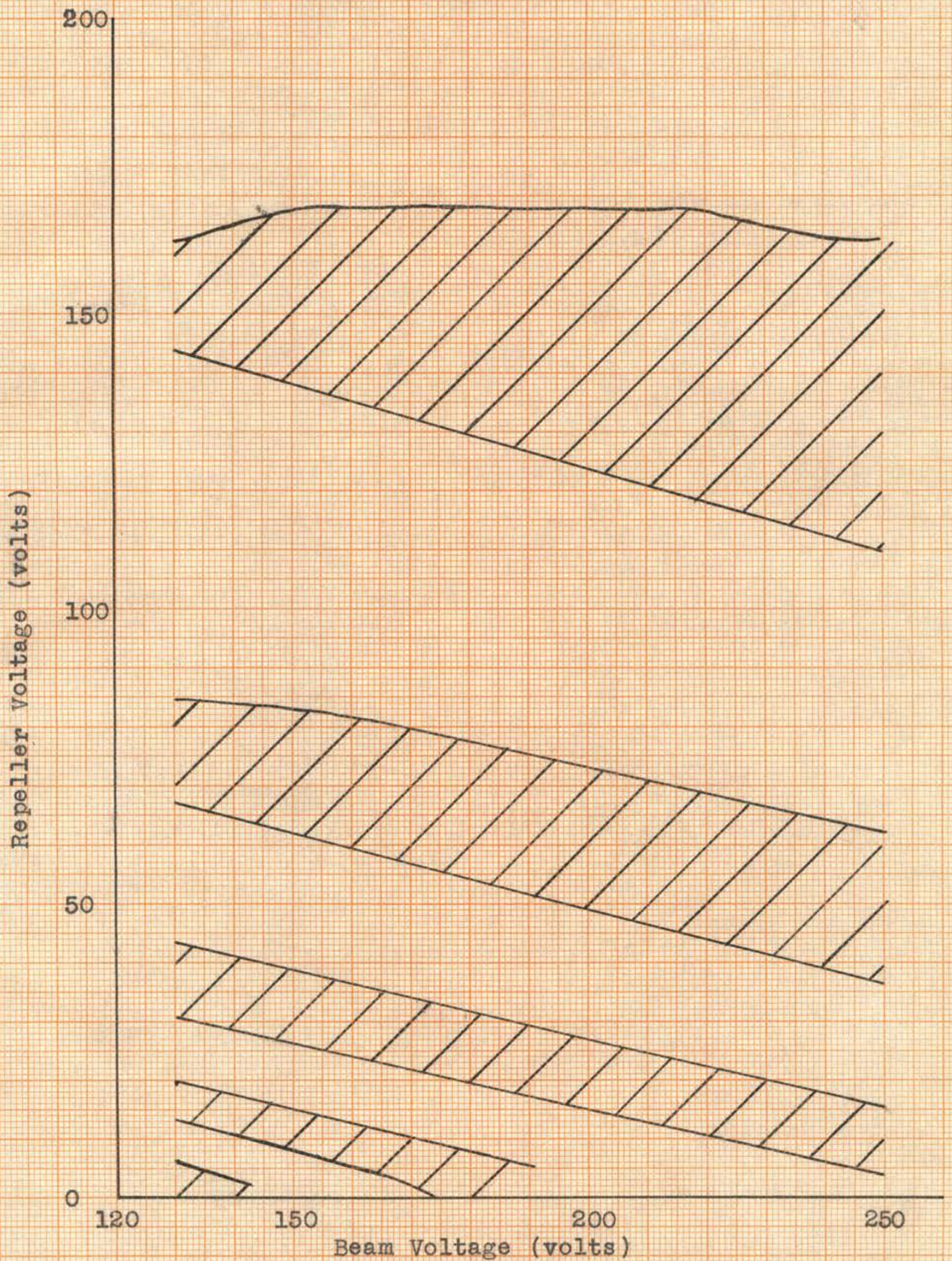


FIGURE 9

evidently corresponds to the lowest bunching time, since high repeller voltage would reverse the electron stream in the shortest time. Mode number corresponds to the next lowest bunching time, etc. There are no modes detected at higher repeller voltages, up to 300 volts D-C negative.

The beam voltage was decreased in steps of 10 volts D-C, beginning at 250 volts D-C, until output readings were too weak to be satisfactory, and at each step the repeller voltage was varied from 300 volts to 0 volts D-C. The Mark S22 detector-wavemeter, placed in the radiated field, was used to detect oscillations. Repeller volts were recorded at points where oscillation began, and at points where oscillation stopped. The frequency of oscillation was approximately 3000 megacycles/second.

E. <u>Power and Frequency Characteristics of Modes of Oscillation with Change in Repeller Voltage</u>

Three sets of data were taken for this experiment. First, for a frequency at the low end of the range, approximately 2900 megacycles/second; second, for a frequency in the middle of the range, approximately 3100 megacycles/second; and third, for a frequency at the high end of the range, approximately 3400 megacycles/second. These frequencies were set by the cavity tuning screws.

For all data the beam voltage was 250 volts D-C, and the oscillator was working into a 4.8 cm. antenna with

POWER AND FREQUENCY CHARACTERISTICS OF MODES OF OSCILLATION WITH CHANGE IN REPELLER VOLTAGE

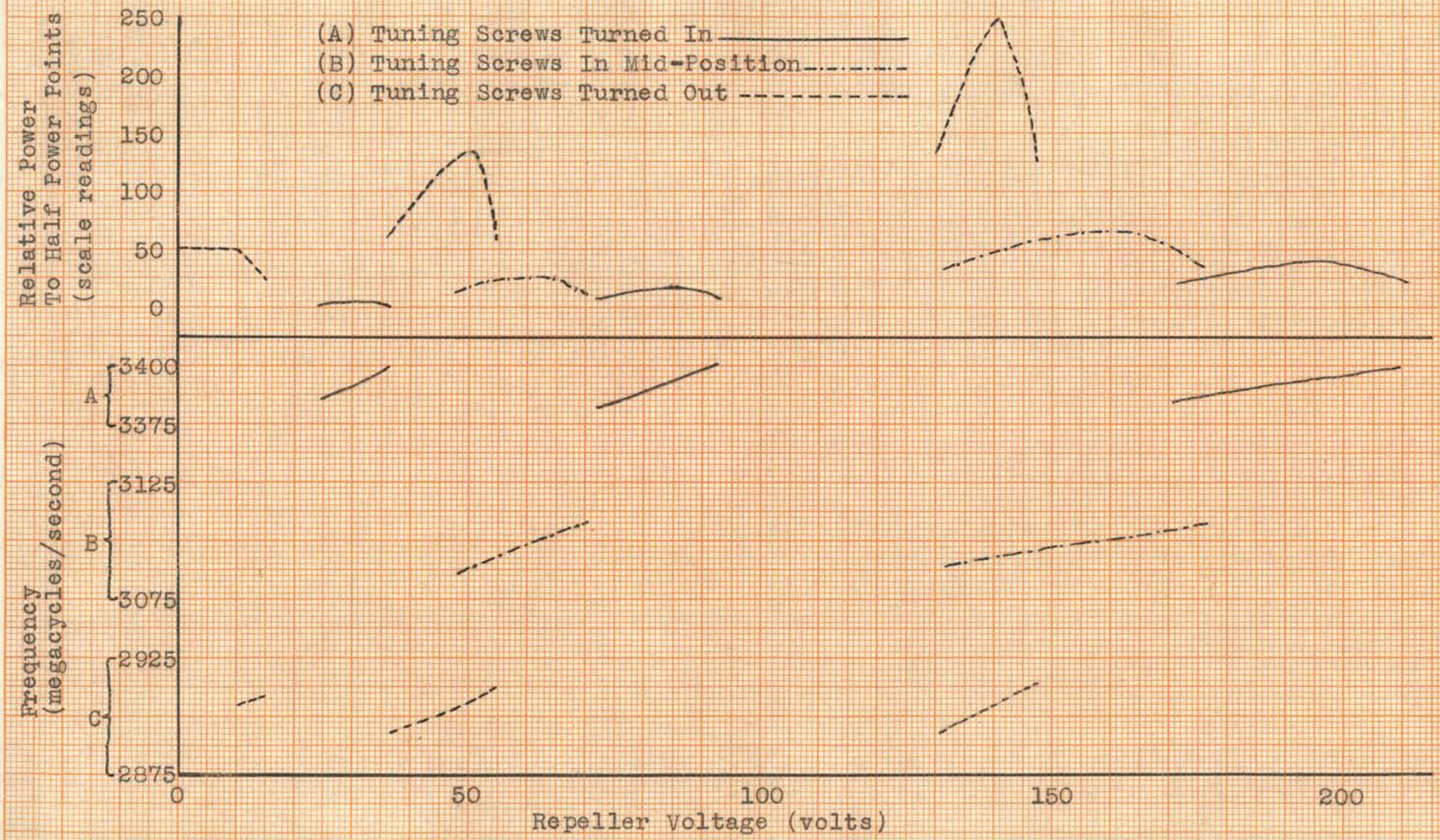


FIGURE 10

reflector. Frequency and relative power were measured by the Mark S22 detector set in a field node position, approximately 10-15 cm. from the transmitting antenna, which would give convenient scale readings. It was noted this node position did not change enough to observe, for frequency changes produced by changes in repeller voltage. The position did change over the large frequency changes produced by the cavity tuning screws. Hence, any one set of data may be assumed valid, but cannot be correlated too closely with the other sets of data.

For each set of data the repeller voltage was adjusted to give a maximum output at a mode of oscillation, say mode 1, this voltage and the frequency being recorded. The repeller voltage was then changed above and below this point to such values as would give $\frac{1}{2}$ the relative power output of the peak of this mode. These voltages and the frequencies were recorded. This procedure was repeated for each mode of oscillation.

The above procedure was followed for each set of data, which is taken at a given position of the cavity tuning screws.

Figure 10 shows the frequency change vs. repeller voltage, and the relative power output vs. repeller voltage for each mode, and each set of data. The graph indicates the corresponding curves for a particular set of data.

F. Cavity Tuning

With the beam voltage maintained at 250 volts D-C, and the vernier tuning adjustment at 1 turn out (median position), the 4 tuning screws were turned from 0 position (full in) to 18 full turns out, in 1 turn steps. At each step the repeller voltage was adjusted for maximum output. The tuning screw position, frequency, and the repeller voltage for maximum output were recorded. The results are shown in figure 11.

The frequency curve shows frequency plotted against tuning screw position. The frequency change is more rapid at the higher frequency end than at the lower frequency end, per turn of the tuning screws.

The repeller voltage curves show the repeller voltage necessary for maximum output plotted against tuning screw position. In general the repeller voltage is seen to rise with increase in frequency. This is to be expected since the bunching time must decrease with increase of frequency.

Three sets of repeller voltage curves are shown, each for a different antenna load. The three sets of data were obtained because the first curve obtained showed a distinct variation from a smooth curve. An explanation of these humps in the curve was needed, hence the experiment was repeated with different antenna loads to determine if the antenna load was an important factor in these humps.

CAVITY TUNING

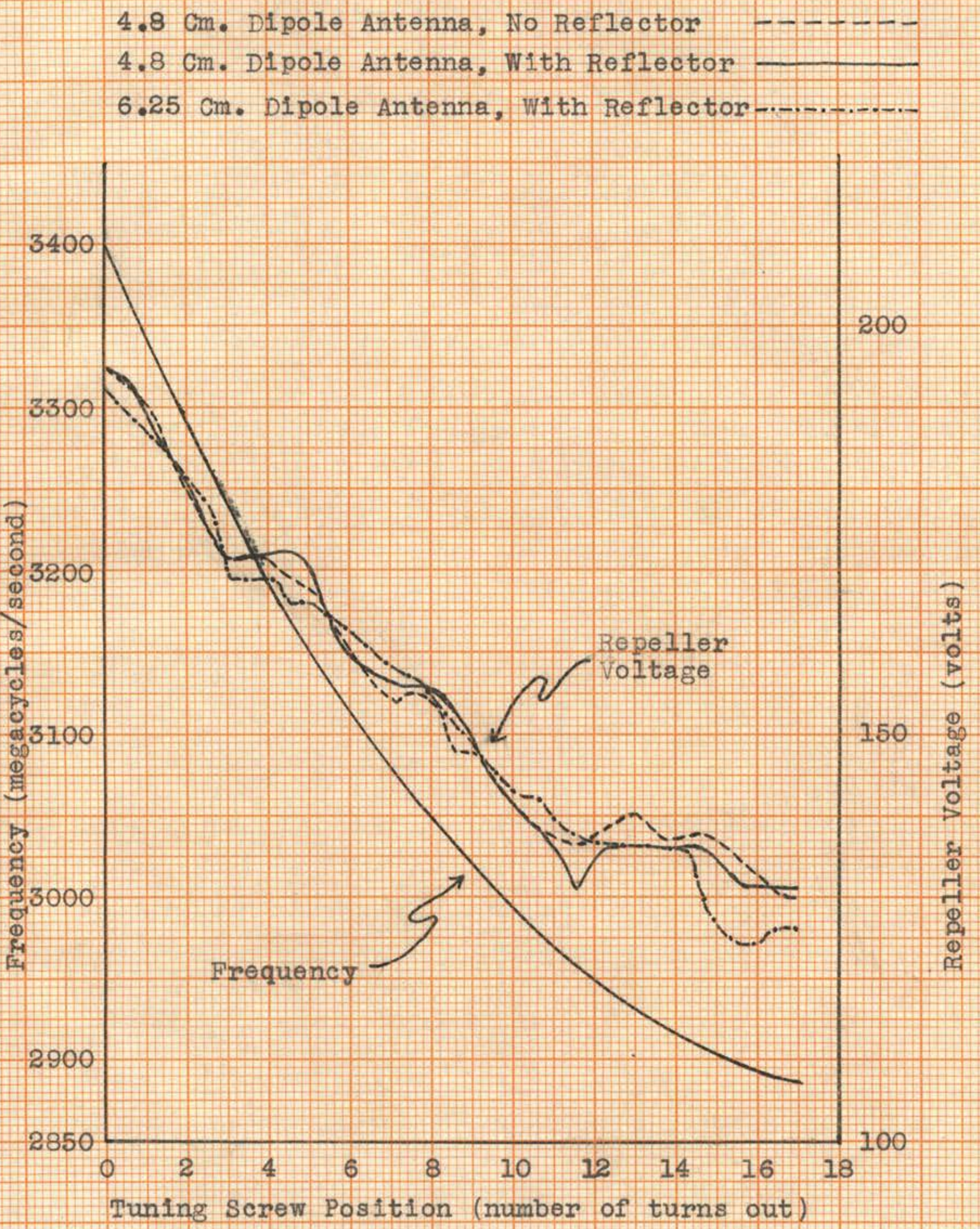


FIGURE 11

The two 4.8 cm. antenna curves agree closely with each other. The 6.25 cm. antenna curve agrees with the 4.8 cm. antenna curves in general shape, but the humps are not as prominent. This is to be expected since the resonant frequency of the longer antenna, in the order of 2400 megacycles/second, is so far removed from the frequencies with which we are working that it has a broadening effect on the output. It is to be definitely noted that the humps in all three curves occur at the same frequencies in spite of the change in load.

An inspection and correlation of figure 11 with figure 13 shows that the frequencies of the humps in figure 10 correlate closely with the frequencies of the humps in figure 13. Further it was noted and recorded that for the tuning screw positions at which these humps occurred the maximum output could be obtained over a range of repeller voltages. Thus the curves at these places assume a certain amount of uncertainty.

A low Q circuit, obtained by tighter coupling to the antenna load, could explain both the increased power output and the broad response to change in repeller voltage at these points. A low Q occuring at only certain frequencies could be explained by considering the configuration field in the cavity. This field changes as the frequency changes. The antenna load coupling is a fixed inductive loop, and if at certain frequencies the loop is in a portion of the field of maximum magnetic flux, and at other frequencies in a portion of minimum magnetic flux, the coupling would vary from tight to loose respectively. A tighter coupling would reduce the Q of the resonant circuit, resulting in broad resonance, and at the same time couple more energy to the antenna.

G. Vernier Tuning

This data was taken to determine the effectiveness of the vernier adjustment in tuning at the high frequency end, median frequency, and low frequency end of the cavity range. The main running screws were used to determine the approximate frequency, then held constant while data was taken by moving the vernier adjustment. Vernier position and frequency were recorded.

The beam voltage was held constant at 250 volts D-C. The repeller voltage was peaked with the vernier at 1 turn out (median position then held constant as the vernier was varied.) The Mark S22 was used as the frequency meter.

One set of data was taken for resetting of the repeller voltage at each position of the vernier, for the median frequency. This showed a slight increase in frequency range.

The vernier gives a frequency range of 75 to 100 megacycles/second.

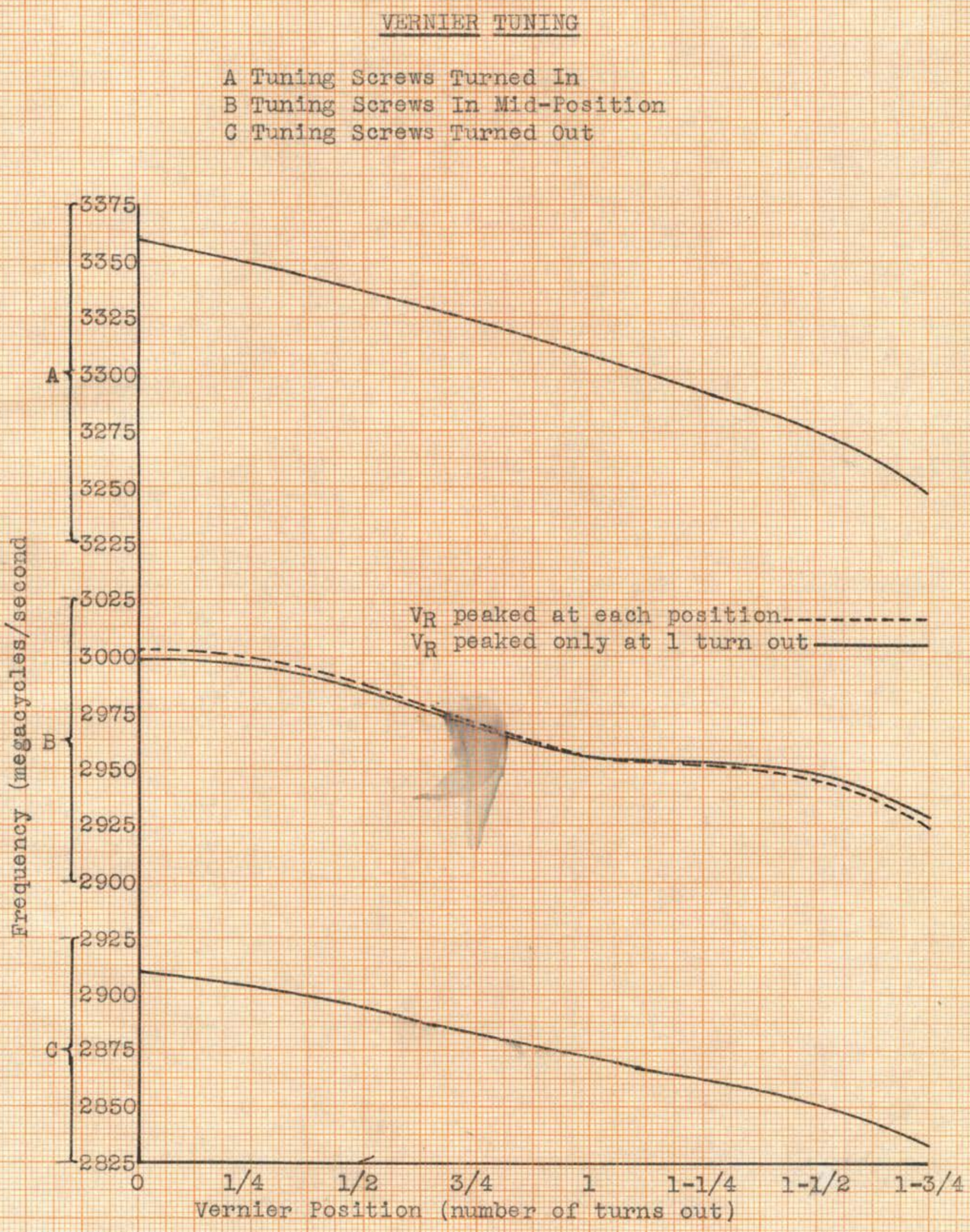
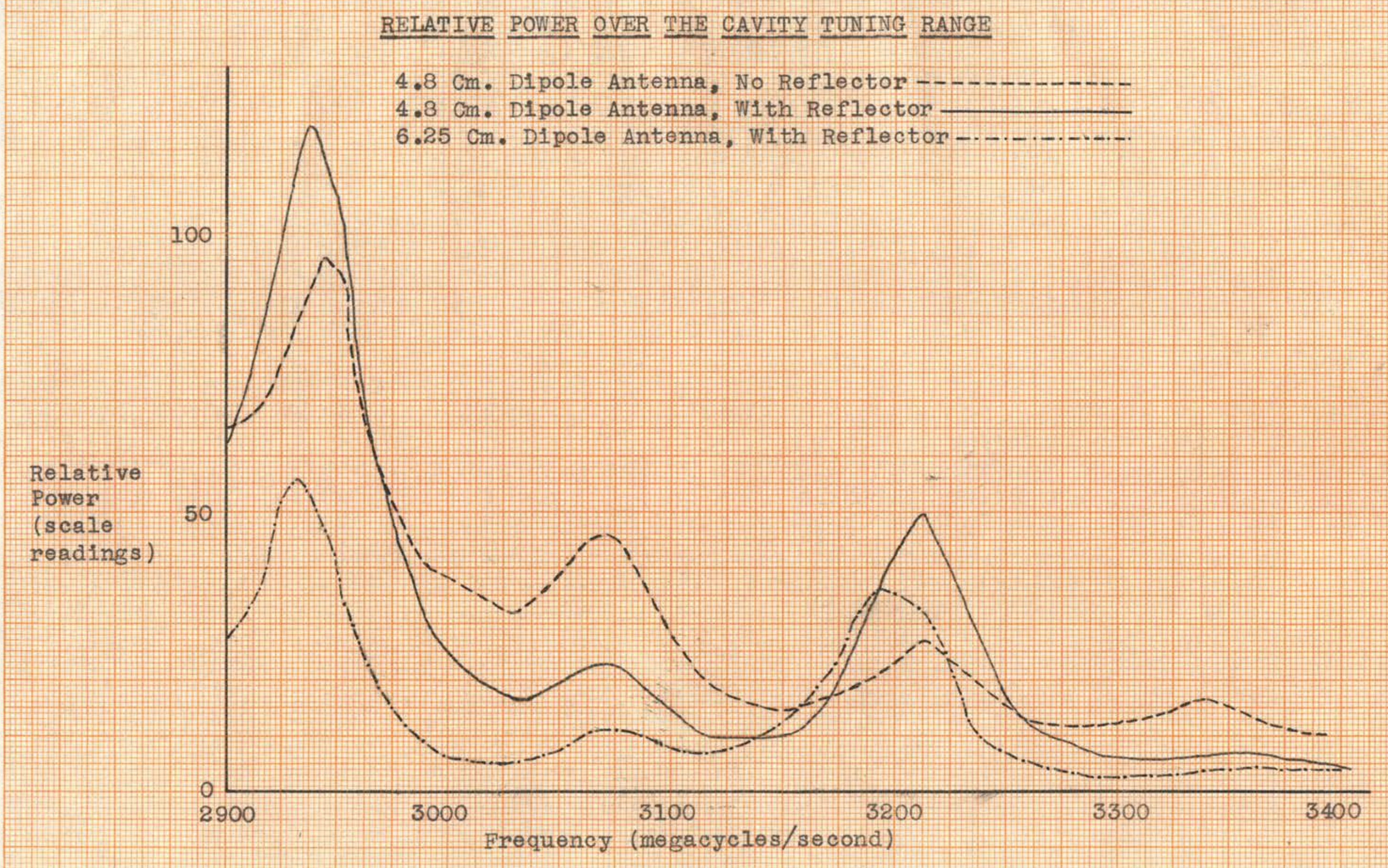

VERNIER TUNING
A Tuning Screws Turned In
B Tuning Screws In Mid-Position
C Tuning Screws Turned Out
3375
3350
3325
A 3300
3275
3250
3225
3025
3000
2975
B 2950
2925
2900
2925
2900
C 2875
2850
2825
V_R peaked at each position
V_R peaked only at 1 turn out
Frequency (megacycles/second
0
1/4
1/2
3/4
1
1-1/4
1-1/2
1-3/4
Vernier Position (number of turns out)

FIGURE 12

H. Relative Power Over the Cavity Tuning Range

For the measurement of relative power, with wide range of frequency, different tests were made.

(1) The transmitting antenna consisted of a 4.8 cm. dipole, with parabolic reflector. The relative power meter was placed at a distance of 50 cm. from the transmitting dipole, and relative power meter scale readings noted for each frequency setting. At this distance the position of the node was found to vary by not more than 2 cm. Over the complete range of frequencies the receiving antenna remained between 48 cm. and 50 cm. from the radiating dipole. The receiving antenna was repositioned, at each frequency, to the node closest to the 50 cm. from the transmitting antenna. Since this 2 cm. is only 4% of the 50 cm. total distance, and the power in a radiated field is inversely proportional to the square of the distance from the antenna, then the relative power reading should be accurate to within 2%, factors other than distance excluded. Since all measurements were taken at a single node, there should be no error due to the standing waves, only to the distance necessary to reposition the receiver to a node, with change in frequency.



RELATIVE POWER OVER THE CAVITY TUNING RANGE
4.8 Cm. Dipole Antenna, No Reflector
4.8 Cm. Dipole Antenna, With Reflector
6.25 Cm. Dipole Antenna, With Reflector
Relative Power (scale readings)
100
50
0
2900
3000
3100
3200
3300
3400
Frequency (megacycles/second)

FIGURE 13

(2) The transmitting dipole was changed to 6.25 cm., and measurements made as in (1) above.

(3) A 4.8 cm. dipole transmitting antenna was used with no reflector. This was found to eliminate the standing waves. The relative power meter was placed 10 cm. from the 4.8 cm. dipole (the field was not strong enough to give satisfactory scale readings at 50 cm.), and relative power scale readings noted for each frequency setting. This method eliminates errors due to repositioning for nodes, but the possibility of error due to random reflected waves increases.

There is no means of measuring the degree of such reflection. However, since the power meter dipole was only 10 cm. from the transmitting dipole, and the closest objects to give reflection were in back of the transmitting antenna a distance of at least 25 cm. it is thought that reflected waves reaching the power meter antenna would be so comparatively weak as to be insignificant. It would be necessary for the reflected wave to travel a total distance of 60 cm. from the transmitting antenna to the power meter antenna, as compared to a direct path of 10 cm.

For all of the above methods the beam voltage was maintained at 250 volts D-C, and the repeller voltage changed at each frequency to give the maximum output. See figure 12 for results obtained.

There can be no correlation between the three curves in terms of relative power, since the detector meter was placed at different distances for the different curves, and also because the field contained nodes when using the reflector, and no nodes without the reflector. The general shape of the curves correlate very closely, however, with the peak outputs occuring at the same frequencies for each curve. The change in antenna load evidently has only a minor effect on the shape of the power output curves.

The possible reason for the three peaks on the curves has been discussed under "Wide Range Cavity Tuning".

BIBLIOGRAPHY

Brainerd, Koehler, Reich, and Woodruff. Ultra-High-Frequency Techniques. New York: D. Van Nostrand Co., Inc., 1943.

Bronwell and Beam. Theory to Application of Microwaves. New York: McGraw-Hill Book Co., Inc., 1947.

Ginzton and Harrison. "Reflex Klystron Oscillators." Proceedings I. R. E. 34(March, 1940), 97.

Hamilton, Knipp and Kuper. Klystrons and Microwave Triodes. New York: McGraw-Hill Book Co., Inc., 1948.

Montgomery, Carol G. Technique of Microwave Measurements. New York: McGraw-Hill Book Co., Inc., 1947.

Pound, Robert V. Microwave Mixers. New York: McGraw-Hill Book Co., Inc., 1948.

Typed by: Mrs. Anthony Banes