Vacuum Tubes as High-Frequency Oscillators *

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Vacuum tubes as oscillators and amplifiers at frequencies greater than 100 megacycles (3 m.) are considered in this paper. The type of construction used in a large number of different tubes, and the characteristics of the tubes, are presented. Circuits for operating the tubes also are considered and the theory of operation and the factors limiting ultra-high frequencies are discussed. Principal attention is given to the tubes as oscillators, with brief consideration of the problem of amplification.

THE three types of oscillation generators which at present are the most efficient in the range from 100 megacycles to 3000 megacycles per second will be discussed in the following survey. These are: the negative grid tube which at lower frequencies is the conventional regenerative oscillator, the positive grid or Barkhausen oscillator, and the "magnetron" oscillator. The amplification problem will be briefly discussed. Because of the present unsettled state of the theory, only the most elementary and generally accepted part will be included. Much theoretical and experimental work remains to be done before knowledge of the mechanism of oscillation and amplification in this frequency range will be satisfactory. As is often the case, the empirical knowledge of some of these mechanisms has outdistanced the theoretical interpretation.

The Negative Grid Oscillator

The conventional thermionic vacuum triode, whether it be a large water-cooled power tube or a small receiving tube, may be used as a generator of oscillations varying in frequency from a few cycles per second to some 20 or 30 megacycles with substantially undiminished efficiency and output. In this range the frequency at which a tube is to be employed is a factor of almost negligible importance in the determination of its characteristics and its form. Beyond this range, however, frequency plays an increasingly important part, and as one approaches 300 megacycles, it becomes the most important factor in the determination of tube design.

When an attempt is made to operate a standard triode at increasingly high frequencies it is found that the output and efficiency begin to decrease. The frequency at which this is first observed will depend

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upon the design of the tube but it will usually be in the 10- to 60-megacycle range. By successive modifications of the circuit arrangement and size this decrease in power output and efficiency can be minimized. With optimum circuit arrangements, however, this decrease continues until finally a frequency is reached beyond which oscillations can no longer be produced.

In Fig. 1 are shown typical data for a standard 75-watt tube, the Western Electric type 242*A*, operated with reduced potentials over

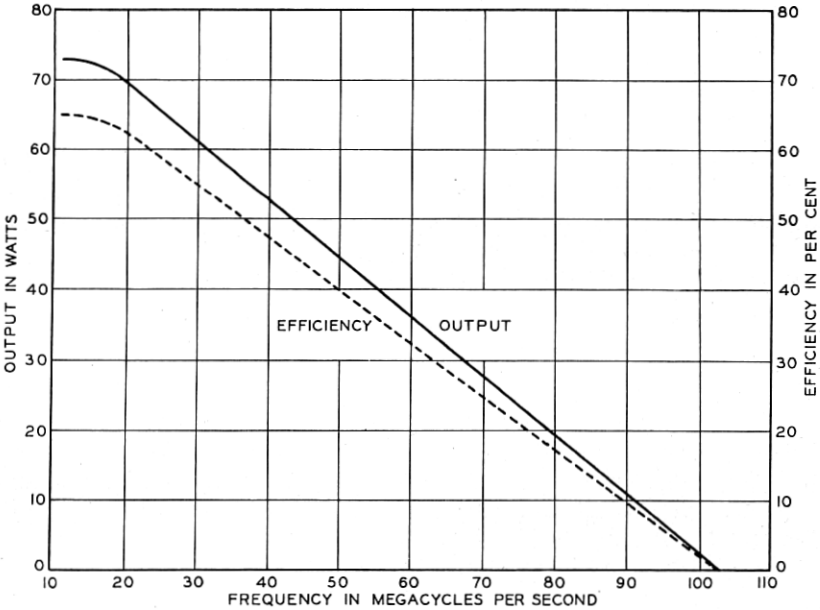


Fig. 1—Power output and anode efficiency as a function of frequency for a standard triode. These curves are typical of all tubes as they approach their upper limiting frequency.

the frequency range from the point where oscillation frequency noticeably affects performance to the point where oscillations can no longer be produced. The plate potential was held constant at 750 volts throughout the entire frequency range. The oscillation circuit was modified at each point in order to obtain maximum output and efficiency, keeping the anode dissipation within the maximum rating of 100 watts and the anode current within the maximum rating of 0.150 amp. It can be seen from the curves that the output and efficiency are independent of the frequency until about 20 megacycles is reached, when they begin to decrease. At 100 megacycles the output power is only 2.5 watts and the efficiency only 2 per cent. The tube will not oscillate at 105 megacycles.

Effect of Energy Losses on Performance

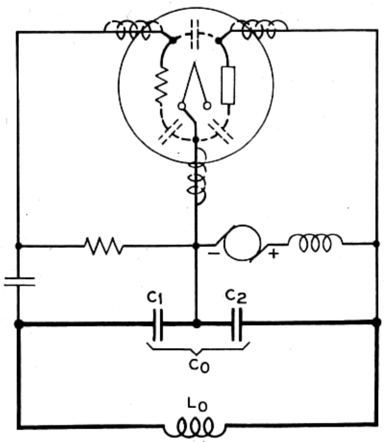
A tube operating in the range where frequency affects performance must withstand energy losses, and the resulting heating within its structure, which occur to only a negligible degree at the lower frequencies. Some of these losses are due to dielectric hysteresis in the insulating materials of the tube, particularly in the portions of the glass supporting stem or bulb which lies between the tube leads. The glass is sometimes so softened by the heat thus developed that it is punctured by the outside air pressure. Losses also occur in the auxiliary metallic parts of the tube structure due to the increased eddy currents that occur at high frequencies. Losses in the tube electrodes and their lead-in wires are also greatly increased due to skin effect which increases their resistance, and due to the increased charging current required by the inter-electrode capacitances. The increased lead temperature, depending upon its amount, will cause a more or less rapid deterioration of the lead-to-glass seals which may ultimately destroy the vacuum. In order to protect the tube from damage because of these new types of energy dissipation, the operating potentials and currents must be reduced to values less than those established for low-frequency operation. Some manufacturers are now giving special ratings on such of their standard tubes as may be used at ultra-high frequencies. These ratings should be adhered to when operating in this range.

Effect of Circuit on Performance

The decrease in output power and plate efficiency which sets in with the increase in frequency, while due in part to the losses described above, and to the rapid increase in radiation losses, is also due to two additional effects of fundamental importance. The first to become evident, with increasing frequencies, is circuital in nature. This can be explained by reference to the conventional oscillator shown in Fig. 2. The frequency of such an oscillator is given by

$$f = \frac{1}{2\pi\sqrt{LC}},$$

where L and C are the effective inductance and capacitance of the oscillating circuit. In the lower frequency range, the LC product which determines the frequency is substantially equal to L_0C_0, that is, to the product of the inductance and capacitance of the external circuit. The inductance of the tube leads and the capacitance between its electrodes (indicated by the dotted lines in the figure) play a negligible rôle. In order to tune the circuit to higher and higher frequencies, the capacitance C_0 is first reduced and finally eliminated, leaving the inter-electrode capacitance as the only capacitance in the oscillating circuit. The tube leads then form a part of the main oscillating circuit, in which large circulating currents must exist for stable operation. For a further increase in frequency the external inductance L_0



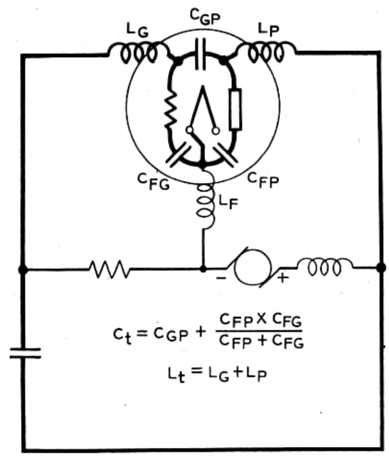


Fig. 2 (left)—A standard Colpitts oscillator circuit. The heavy lines indicate the main oscillating circuit. The dotted portions represent the inter-electrode capacitances and lead inductances which play a minor rôle at low frequencies.

Fig. 3 (right)—The limiting circuit with the external tuning capacitance eliminated and the external inductance reduced to a short circuiting bar between the grid and plate leads. The main oscillating circuit, indicated by the heavy lines, is seen to include the inter-electrode capacitances and lead inductances.

must be reduced and, in the limit, it becomes the shortest possible connection between the grid and plate terminals. The oscillating frequency for this limiting circuit, shown in Fig. 3, is determined by the product of the lead inductance L_t and the inter-electrode capacitance C_t; that is,

$$f_0 = \frac{1}{2\pi\sqrt{L_t C_t}},$$

where L_t is the sum of the grid and plate lead inductance and C_t is the total grid-plate capacitance. Even before this frequency limit is reached the output power and plate efficiency are seriously reduced by the lack of full control over the relative amplitude and phase of the alternating grid and plate potentials. Whereas the ratio of these amplitudes is controlled in the circuit shown in Fig. 2 by the condensers C_1 and C_2, it is determined in the limiting case primarily by the fixed ratio of the grid-filament to plate-filament inter-electrode capacitance. Most tubes made especially for ultra-high-frequency use are constructed so as to minimize these circuit limitations by a reduction in the inter-electrode capacitance and lead inductance and by adjusting the capacitance ratio.

Effect of Transit Time on Performance

The second fundamental effect has to do with the time required for the electrons to travel from the cathode to the anode within the tube structure. This time, the so-called transit time, is very small in present-day commercial types of power tubes, usually much less than one micro-second. Obviously at low frequencies it can be neglected and, in fact, for many tubes it still plays a minor rôle either in determining the output and efficiency in the high-frequency range or in establishing the limiting frequency for oscillations. When the frequency range of oscillation of a tube is extended by an adequate decrease in energy losses and by improvements in electrical design, transit time becomes a dominating factor in the reduction of output power and efficiency and in establishing the limiting frequency of oscillation.

This comes about in two ways. In the first place, the relative phase of the alternating grid and plate potentials for best operation must be altered to compensate for the time required for the electrons to travel from the region in which the grid has its greatest effect upon their motion to the region in which their motion has the greatest effect upon the plate current. The available control over these phases is usually insufficient to permit a realization of the optimum adjustment. In terms of the measured characteristics of the tube, the transconductance has become complex. But even with the optimum phase adjustment the efficiency is reduced by losses which occur because of the variations in grid and plate potentials during the transit time. Electrons arriving at the plate will in general have velocities greater than the velocity corresponding to the potential of the anode at the instant of their arrival. The excess energy corresponding to the greater velocity is obtained from the oscillating circuit and is dissipated at the plate in the form of heat. Again in terms of the measured characteristics, the input conductance has been increased above its low-frequency value.

The mechanism which enables electrons to take energy from the oscillatory circuit in their passage across the tube is evident from a consideration of a somewhat simplified case as shown in Fig. 4. Assume that the anode is held at a constant positive potential of 100 volts, and that the grid is held at 50 volts positive just long enough to allow an electron to come from the cathode to the grid plane (very near one of the wires), where its velocity will correspond to a fall of 50 volts. The potential of the grid is then suddenly changed to 50 volts negative. The electron will then fall through an additional potential difference of 150 volts, arriving at the anode with a velocity corre-

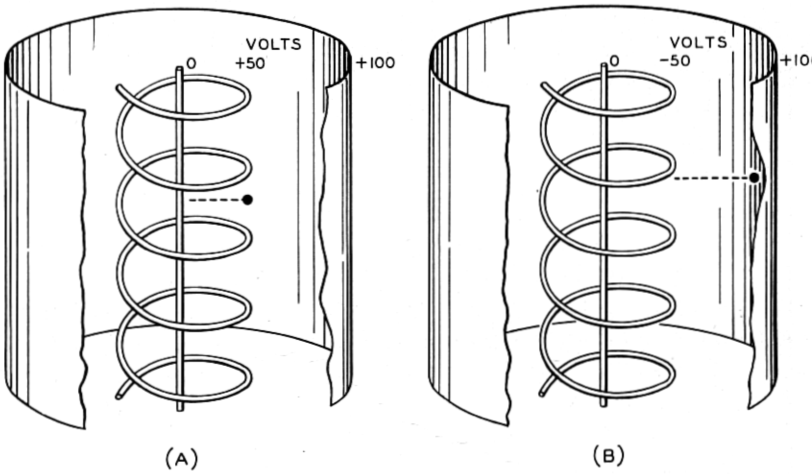


Fig. 4—Illustrating the mechanism which enables electrons to take energy from the oscillating circuit.

sponding to 200 volts, producing just twice as much heat as it would have done had the grid potential not been changed during the transit time. This added energy must come from the source which produced the change in the grid potential. In the actual case the change in grid potential is not abrupt but a similar loss occurs. This limits the useful frequency range of a tube to values for which the oscillation period is long compared to the electron transit time.

Special Designs Required for Different Ranges of High Frequencies

Most standard power tubes reach their upper frequency limit of oscillation somewhere in the 10- to 100-megacycle frequency range. For frequencies above this, specially designed tubes are required. The frequency range in which a given design is near the optimum is limited. Therefore, there is a succession of tubes, each rated for a band of frequencies. Characteristics such as a high mutual conductance and a sharp cut-off which make a tube a good oscillator at low frequencies, while still of importance at ultra-high frequencies, are apt to be secondary to the special frequency requirements

Although some progress has been made in the modification of conventially designed water-cooled tubes for use above 100 megacycles, more attention has so far been given to the development of radiation-cooled tubes for this frequency range.

A departure from conventional design with increasing frequency is illustrated by a radiation-cooled tube described by McArthur and Spitzer [1] in which the ratio of the plate diameter to the plate length

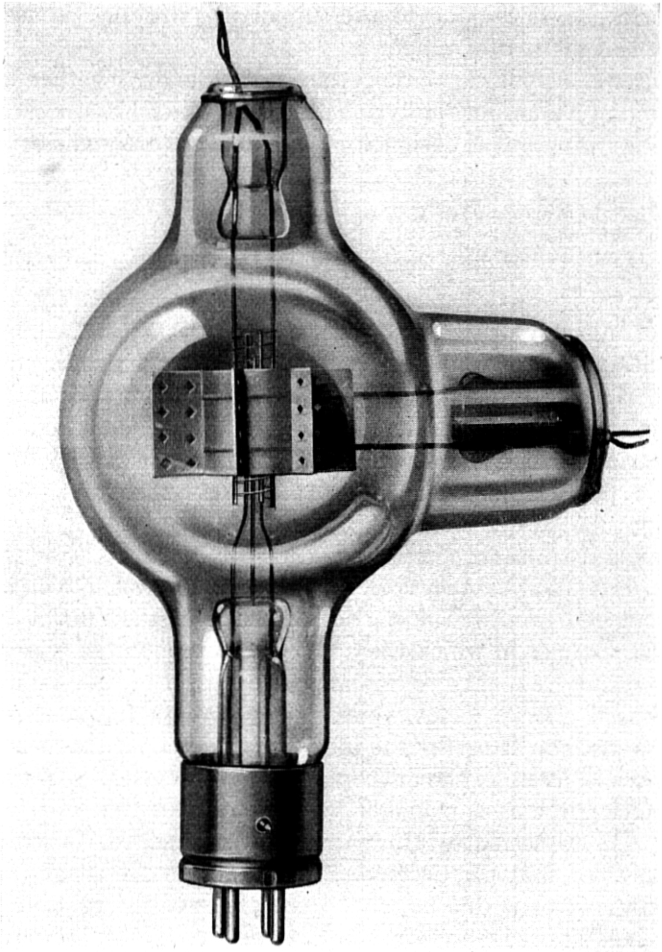


Fig. 5—A radiation cooled tube for use in the frequency range from 60 to 180 megacycles per second. Note the large ratio of the plate diameter to plate length and the special arrangement of the leads.

[1] For all numbered references see list at end of paper.

is much larger than for the conventional tube. Radiating fins are employed to compensate for the decrease in heat radiating ability of the plate which would otherwise occur because of its short length. In Fig. 5 is shown a photograph of this tube. It will be noted that the tube electrodes are supported directly from their leads. The complete absence of auxiliary supporting members either of metal or of insulating material and the large size of leads reduce radiation, eddy current, and conduction current losses. That portion of the inter-electrode capacitances due to the supporting structure is also made small by this method of support.

The inter-electrode capacitances are given below, together with the corresponding values for the type 242*A* tube, which has the same plate dissipation rating but is designed for use at lower frequencies:

	High Frequency Tube	242*A*
Plate to grid	3 $\mu\mu$f	13.0 $\mu\mu$f
Grid to filament	2 $\mu\mu$f	6.5 $\mu\mu$f
Plate to filament	1 $\mu\mu$f	4.0 $\mu\mu$f

The decrease in capacitance by a factor of approximately 4 makes possible a much greater improvement in performance in the 60- to 150-megacycle-per-second frequency range than the corresponding degradation in performance due to the lower mutual conductance and the increased electron transit time resulting from the increased spacing. The material increase in plate impedance makes it necessary to employ an anode potential approximately twice as great with the high-frequency tube.

Output and efficiency curves are shown in Fig. 6. (For the sake of uniformity, curves taken from published papers have, in most cases, been redrawn.) The particular shape of the output curve is due to the manner in which the applied anode potential was reduced with increasing frequency to minimize the danger of tube failure from the increased energy losses which occur at high frequencies. The limiting frequency as set by the inter-electrode capacitances and lead inductances is given by the authors as 230 megacycles. An extension of the efficiency curve to higher values indicates that the tube will probably fail to oscillate before this limit is reached. From this it can be inferred that the decrease in efficiency in the range from 150 to 200 megacycles is due largely to the effect of the relatively large transit time, since the authors' method of arriving at the output by taking the difference between the measured input and the measured plate losses includes circuit and lead losses as a part of the output. A comparison of the data of Fig. 1 and Fig. 6 shows that at 100 megacycles the output of the type 242*A* tube is 2 watts and the corresponding output of the high-frequency tube is approximately 86 watts with substantially the same plate loss. This strikingly illustrates the improvement obtained by taking into account the factors which become important in the high-frequency range.

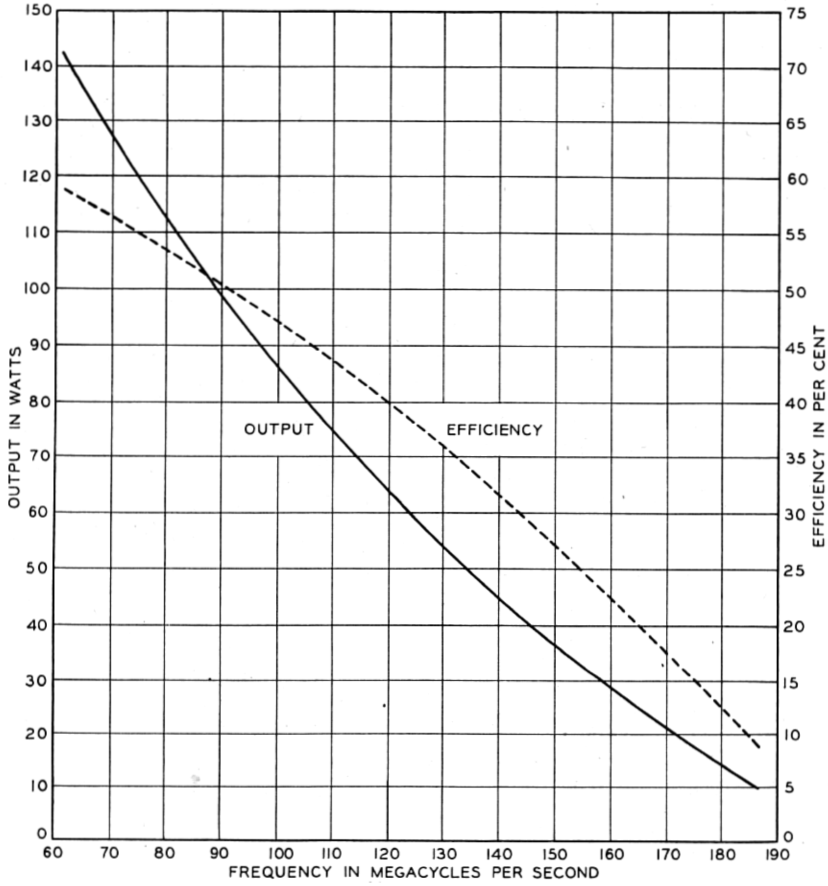


Fig. 6—Output and efficiency as a function of frequency for the tube shown in Fig. 5. A comparison of these curves with those shown in Fig. 1 illustrates the improvement obtained by taking account of those factors which become important at high frequencies.

Transit Time Becomes More Important

In extending the frequency range to 300 megacycles the importance of electron transit time becomes relatively greater. It must be kept as low as possible even at the expense of relatively higher inter-electrode capacitances. In the tube just described for the frequency range around 100 megacycles the reverse procedure is followed; in order to make the inter-electrode capacitances as small as possible, transit times are increased. Fay and Samuel[2] in a recent paper presented before the International Scientific Radio Union (U.R.S.I.) describe a tube designed for use at 300 megacycles which well illustrates this point. The tube is shown in Fig. 7. It differs from the one

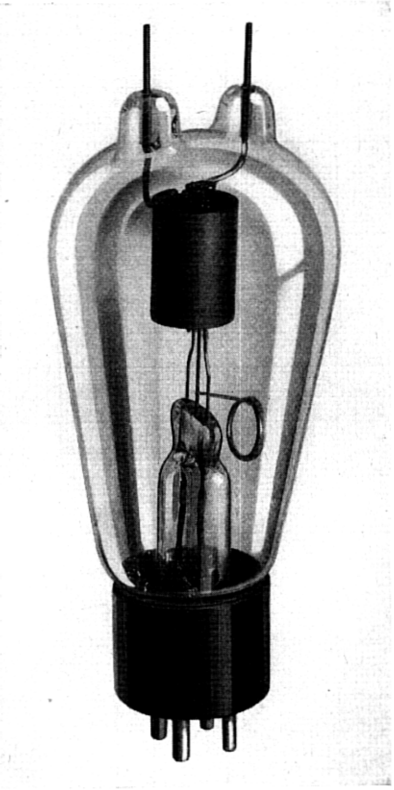


Fig. 7—A tube for use at frequencies up to 350 megacycles.

previously discussed in the close spacings between elements, particularly between the grid and filament. The lead length is further decreased and lead diameter made considerably larger in order to decrease lead inductance and resistance. The inter-electrode capacitances are:

Plate to grid	2.5 $\mu\mu$f
Grid to filament	2.0 $\mu\mu$f
Plate to filament	0.67 $\mu\mu$f

While these capacitances are substantially the same as for the tube shown in Fig. 5, the limiting frequency, as set by circuit resonance, is somewhat beyond 400 megacycles as contrasted with 230 megacycles for the other tube. This is due, primarily, to the material decrease in lead inductance. The decreased losses resulting from the minimized transit time more than compensate for the increased circuit loss resulting from the required higher charging currents to the inter-electrode capacitances. Its mutual conductance of 2200 micro-

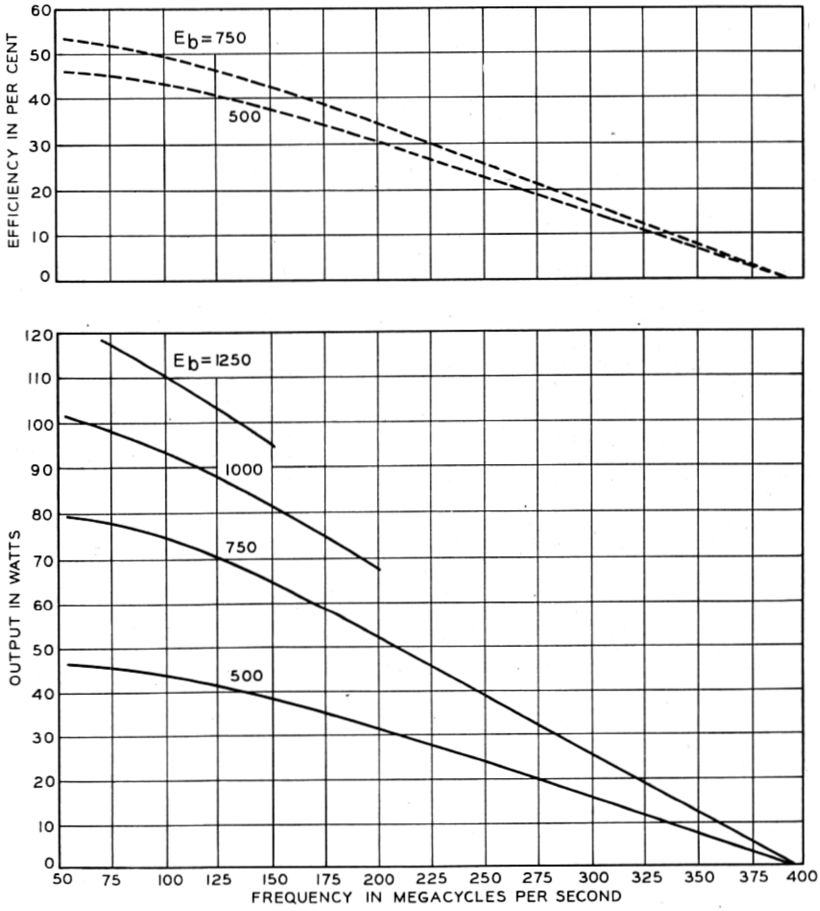


Fig. 8—Output and efficiency curves for 2 tubes of the type shown in Fig. 7.

ohms and the sharp cut-off shown by the static characteristics indicate that those electrical characteristics which are important for efficient oscillators in the low-frequency range have not been sacrificed in meeting the requirements of 300-megacycle operation.

Output and efficiency curves for this tube are shown in Fig. 8.

These data are for two tubes operated in the push-pull circuit shown in Fig. 9. The output shown represents only useful power, since it is the photometrically measured power consumed in a lamp load. It will be noted that, whereas the maximum output at 100 megacycles is 55

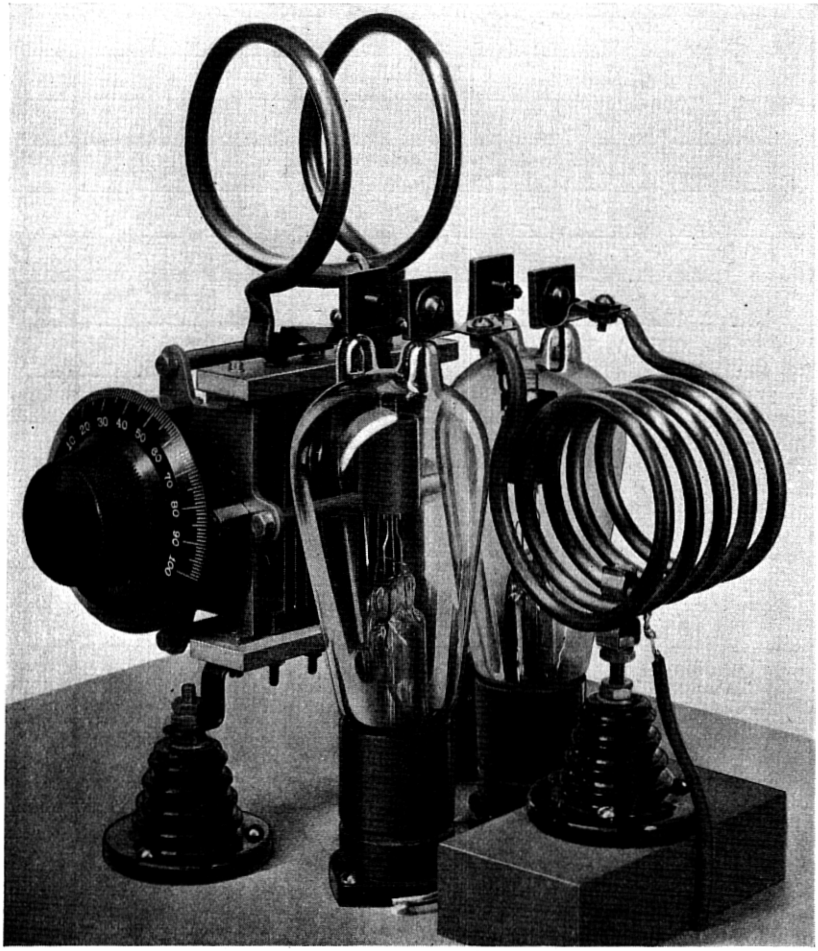


Fig. 9—A typical push-pull circuit for use at ultra-high frequencies. A circuit of this type was used to obtain the data shown in Figs. 8 and 11.

watts per tube and the efficiency 50 per cent, corresponding roughly to the 86 watts output at 47 per cent efficiency for the tube of Fig. 5, the output at 200 megacycles is 34 watts at 33 per cent efficiency as compared to less than 10 watts at an efficiency of only a few per cent for the other tube. At 300 megacycles the higher frequency tube gives an output of 13 watts, while the tube of Fig. 5 no longer oscillates. This difference in behavior is due primarily to the decreases in transit time and in circuit losses, and to the more nearly optimum ratio existing between the inter-electrode capacitances. It is due to a considerably less extent to the increase in the frequency limit set by circuit resonance.

A Still Further Departure in Construction

The tube illustrated in Fig. 10 represents a still further departure from conventional construction with a corresponding increase in the

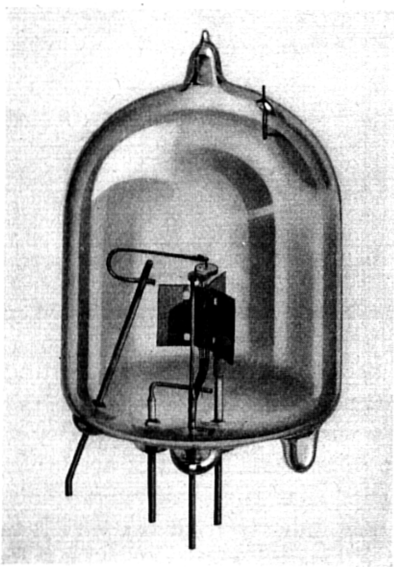


Fig. 10—This tube will oscillate at frequencies up to 740 megacycles. Note the absence of the usual press and the extremely small size of the elements.

frequency limit. Fay and Samuel report an output of 6 watts per tube at 500 megacycles and a frequency limit of 740 megacycles. Unusual features of the design are: The complete elimination of the usual press, the close spacing of the leads and the special construction of the tube elements, particularly the grid, made necessary by their small size. The grid is in the form of a number of straight wires (parallel and equidistant from the axial filament) supported by cooling collars at each end. The plate, in spite of its small size, can dissipate 40 watts with safety.

The inter-electrode capacitances of this tube are:

Plate to grid	1.8 $\mu\mu f$
Grid to filament	1.0 $\mu\mu f$
Plate to filament	0.75 $\mu\mu f$

The output and efficiency curves, shown in Fig. 11, were obtained with two tubes in a push-pull circuit. The efficiency of the tube is

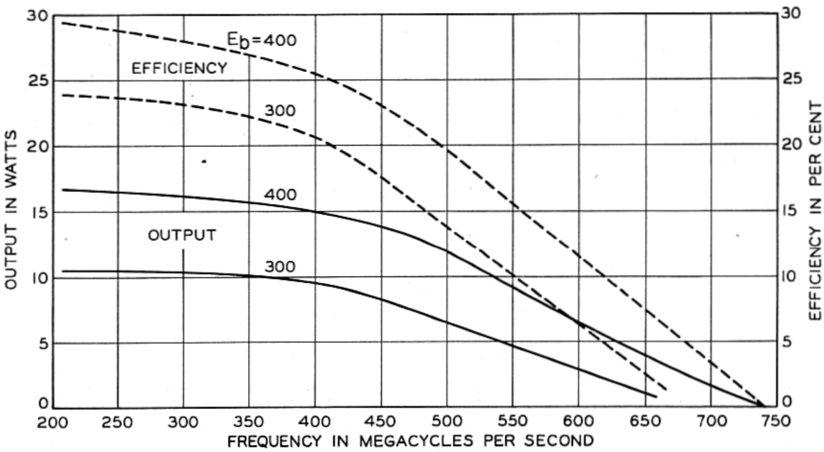


Fig. 11—Output and efficiency curves for 2 tubes of the type shown in Fig. 10.

about 28 per cent at 300 megacycles, contrasting with only 18 per cent for the previously discussed tube, while the output is only 8 watts as compared to 13 watts. The higher efficiency suggests that above 300 megacycles two of the smaller tubes are preferable to one of the large tubes. The fact that the limiting frequency varies with the applied anode potential indicates that the transit time effect is largely responsible for the decreased efficiency. This suggests modulation difficulties if the tube is used near the upper limit of the frequency range. The outputs and efficiencies in the 400- to 600-megacycle range, although low, represent a substantial increase over the usual values obtained at these frequencies.

The relatively low efficiency at 200 megacycles is due to insufficient filament emission. In order to maintain space charge conditions near the filament, at high frequencies, the electron emission must be large enough to supply not only the actual electron current to the plate but also the charging currents to the grid-filament and plate-filament capacitances. In a tube of this small size an increase in the filament emission is possible only by an impractical and unwarranted increase in the filament heating current.

The logical extension of these principles to increasingly high frequencies requires the use of closer and closer inter-electrode spacings. Severe mechanical difficulties are encountered. Curiously enough the limiting factor in the power dissipating ability of the tube turns out to be the grid temperature rather than the temperature of the plate as might be expected. This comes about because of the required close grid-filament spacing, and makes necessary the adoption of some method of cooling the grid. One of the writers has constructed a series of tubes in which the grid is a tungsten helix, each turn of which is attached to a common cooling fin projecting through a slot in the plate. This construction simplifies the mechanical problems involved and provides ample grid cooling. Two of these tubes are shown in Fig. 12.

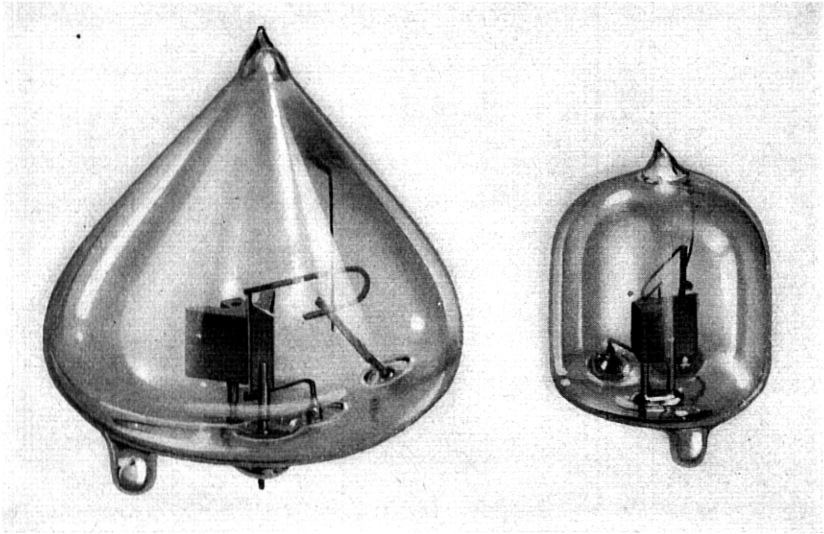


Fig. 12—These tubes represent a further extension in design according to the principles under discussion. The smaller one will oscillate at 1200 megacycles per second.

The larger one will deliver 10 watts at 670 megacycles with an efficiency of 20 per cent and the smaller one will deliver one watt at 1200 megacycles with an efficiency of 10 per cent. These tubes are in no sense commercial, the results representing the limit that has been obtaned by specially constructed tubes under controlled laboratory conditions at voltages and currents above those for which the tube would have a long life. With further advances it is reasonable to expect that outputs of this sort will be commercially realizable and that the frequency range of the negative grid oscillator can be extended beyond 1200 megacycles.

Tubes for Receiving Purposes

For receiving purposes where large outputs are not needed, the ultra-high-frequency requirements may be met by shrinking all the tube dimensions in proportion to the desired wave-length. Tubes constructed by Thompson and Rose [3] based upon this principle are shown in Fig. 13 compared in size with the conventional receiving type tube.

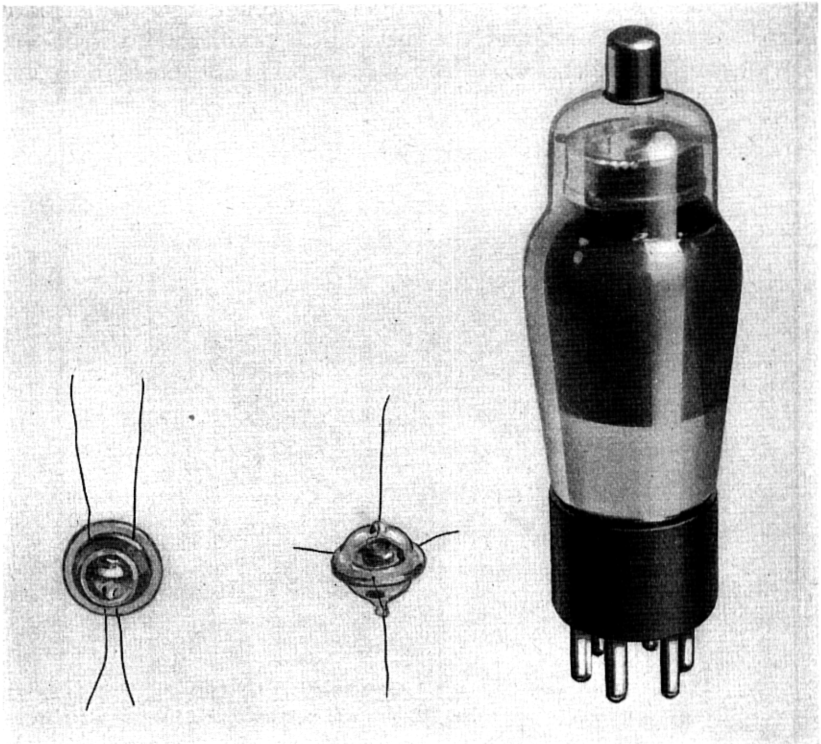


Fig. 13—Receiving tubes of extremely small dimensions. A conventional receiving type tube is shown at the right for comparison.

These tubes make use of parallel plane electrodes, the cathode being oxide coated and indirectly heated, and the grid being in the form of a mesh. A cross-section view of the triode is shown in Fig. 14. This tube will oscillate at frequencies up to 1000 megacycles in miniature replicas of the customary circuits used at longer wave-lengths. A photograph of a complete oscillator is shown in Fig. 15 and the circuit diagram in Fig. 16.

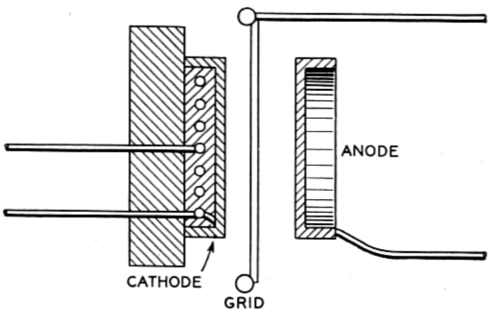


Fig. 14—A sectional view of the triode developed by Thompson and Rose.

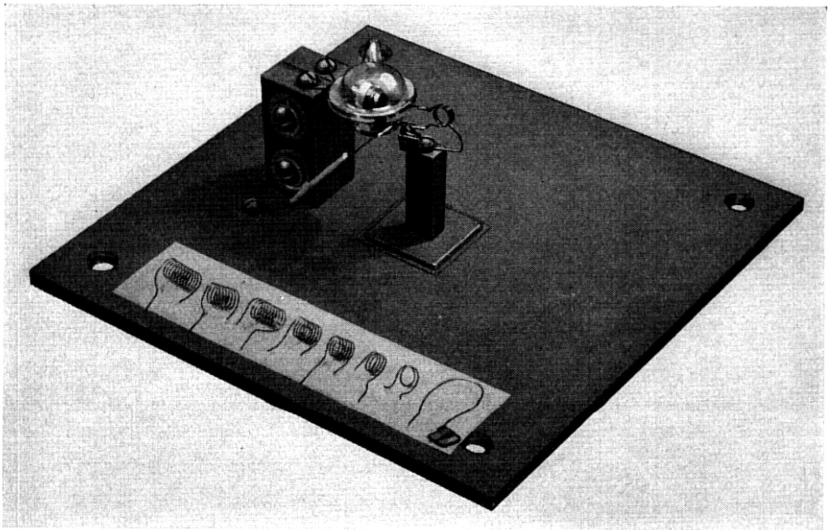


Fig. 15—A complete oscillator using a miniature receiving tube.

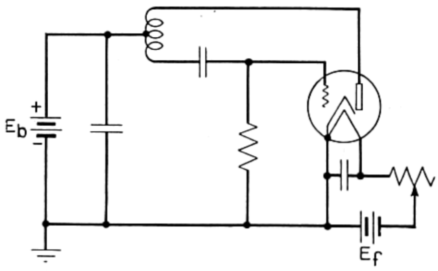


Fig. 16—The circuit diagram of the oscillator shown in Fig. 15.

Factors Limiting Ultra-High Frequencies

The limiting factor in the continued extension of the negative grid oscillator to higher and higher frequencies appears to be the dependence of physical size and output power on the operating frequency range. This dependence is well illustrated by the comparison in Fig. 17 of

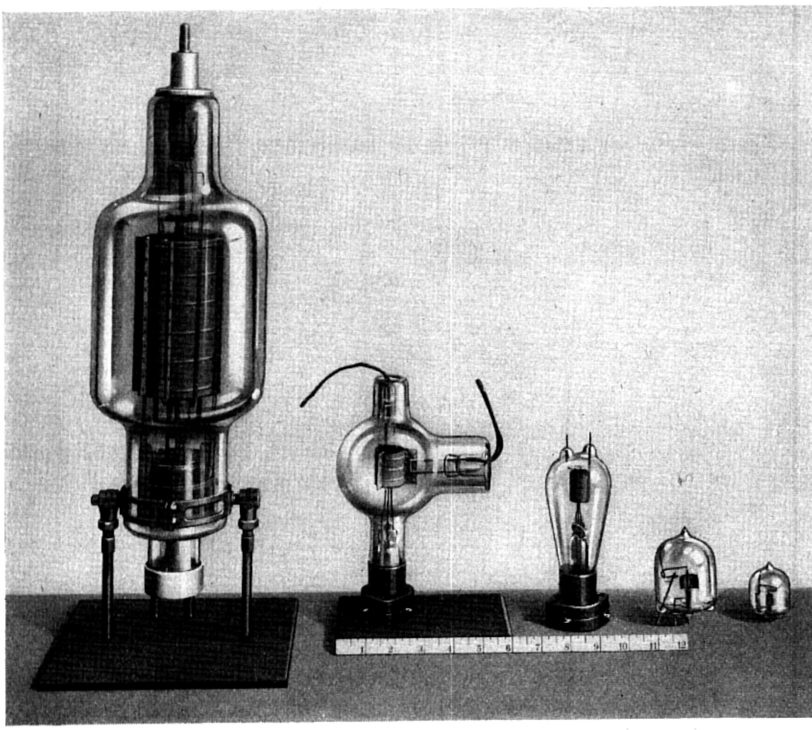


Fig. 17—Some of the tubes, previously discussed, compared in size with a lower frequency tube on the left.

some of the tubes so far discussed with a standard one-kilowatt tube for which the frequency limit is approximately 75 megacycles. Dimensional considerations indicate that the linear dimensions of a series of tubes of optimum design must be decreased in proportion to the operating wave-length. Since the heat dissipating ability depends upon the surface area of the plate, the output (assuming the same efficiency) will decrease as the square of the wave-length. That this is approximately true for the tubes shown in Figs. 5, 7, and 10 may be seen by reference to Fig. 18 where the outputs as a function of frequency are plotted on a logarithmic scale. The sloping lines are for

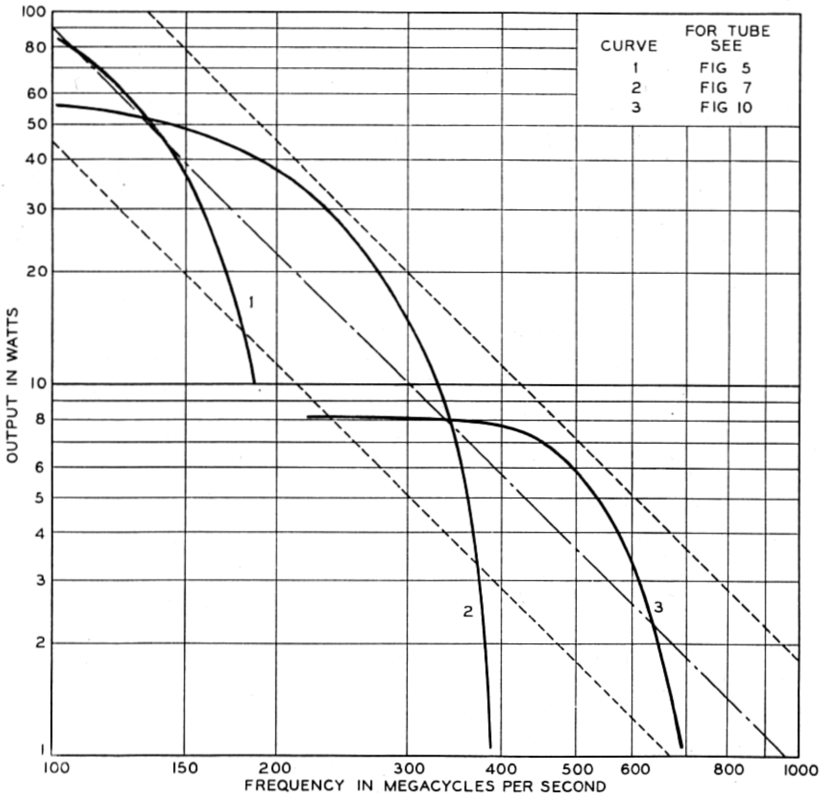


Fig. 18—A comparison plot of the outputs obtained with the tubes of Figs. 5, 7, and 10. The sloping lines are fixed values of the ratio of output to the square of wave-length.

different values of the ratio of output to the square of the wave-length. With radiation-cooled tubes patterned after those illustrated, outputs of only a few tenths of a watt at 3000 megacycles can be expected. If larger outputs are to be obtained, innovations in tube design must be made.

Positive Grid (Barkhausen) Oscillator

As first reported by Barkhausen and Kurz [7] in 1920, oscillations at frequencies greater than 300 megacycles can be produced by most high-vacuum triodes having symmetrical cylindrical structures when the grid is operated at a fairly high positive potential and the plate is held at or near the cathode potential. When so used they are variously known as oscillators of the Barkhausen and Gill-Morell [8] types after the earliest experimenters, or oscillators of the positive grid or retarding field type to designate the arrangement of the electrode potentials. The relative ease with which such oscillations can be obtained at frequencies above 300 megacycles by the use of conventional tubes, and the widespread interest in this frequency range for communication purposes, have led to the appearance of a large number of papers on the experimental and theoretical aspects of such operation.

With the positive grid oscillator there are found to exist preferred frequencies of operation fixed by the electrode spacings and the applied electrode potentials. For the lowest preferred frequency mode of oscillation the relationship is such that the period of one complete oscillation is approximately equal to the total transit time of an electron which fails to strike the grid on its first transit, is retarded and finally turned back by the plate potential, and again missing the grid, returns to the cathode. Under these conditions the relationship,

$$\frac{E_g}{n^2} = \text{constant}$$

is found to hold approximately, where E_g is the applied grid potential, n is the frequency, and the constant is a function of the tube geometry. Other high-frequency modes of oscillation can be obtained. One of these is particularly easy to excite if the grid of the tube is in the form of a simple helix. The important rôle played by the electron transit time in determining the frequency of the positive grid oscillator contrasts sharply with the minor rôle it plays in determining the frequency of the negative grid oscillator.

For maximum output it is necessary to adjust the tuning of the external circuit to correspond to the preferred frequency fixed by the applied electrode potentials. The relative dependence of the frequency upon the circuit tuning and on the applied electrode potentials varies greatly with the design of the tube. In any case the improper adjustment of either parameter results in a marked decrease in output. In general it appears that the better the tube design and the higher the operating efficiency the greater will be the dependence of frequency upon circuit tuning and the less will be its dependence upon the applied electrode potentials.

The most efficient operation of the positive grid oscillator is obtained when the space current is limited by the cathode emission, as contrasted with the most efficient operation of the negative grid oscillator when the current is limited by space charge. Not only must the space current be emission limited but it must have a fairly critical value. This makes it necessary to adjust the cathode temperature critically. Since the cathode emission characteristics are apt to change with time, frequent readjustments of the cathode temperature are usually required.

No completely satisfactory and generally accepted theory of the positive grid oscillator has as yet been given. Many theoretical papers dealing with the mechanism of oscillation have been published. Some of these papers resort to pictorial explanations which, from their very nature, must leave out certain basic factors. Readers interested in a résumé of the various theories are referred to the excellent review by Megaw [13] and to the original papers. It is now recognized that any accurate theory must be based upon a general consideration of all the forces acting upon the electrons in their flight between the electrodes. This may take the form of either a particular solution of the classical electromagnetic equations for the conditions within the tube or an analysis of the energy contributions due to individual electrons in their passage across the inter-electrode space.

Construction of a Positive Grid Tube

A representative positive grid tube of current design described by Fay and Samuel [2] before the International Scientific Radio Union is shown in Fig. 19. This tube differs from the conventional negative grid tube primarily in the construction of the grid and in the arrangement of the leads. While designed primarily for use in the frequency range from 500 to 550 megacycles, it illustrates the general problems encountered in the construction of the positive grid oscillator of this type for any frequency range.

The grid consists of a number of parallel wires supported by cooling collars at each end, the so-called squirrel cage construction. It will withstand 150 watts heat dissipation safely, and provides a minimum of circuit inductance and resistance. The grid diameter is fixed by the frequency for which the tube is designed and by the desired operating potential, such that the relationship

$$d_g = \frac{K_1\sqrt{E_g}}{n} \tag{1}$$

is approximately satisfied, where d_g is the diameter of the grid, K_1 is a constant, n the frequency, and E_g the applied grid potential.

An indefinite increase in output at a fixed frequency by the simultaneous increase in the grid diameter and in the applied grid potential is not possible because of the limited permissible grid dissipation per unit area. The optimum grid current is found to follow roughly a 3/2

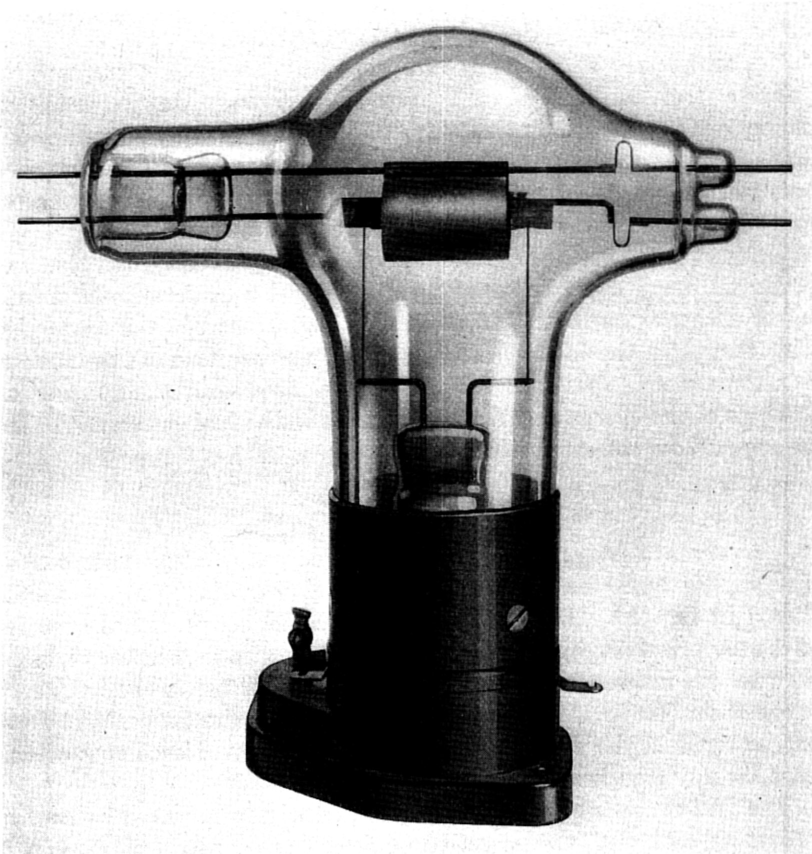


Fig. 19—A positive grid oscillator designed for the frequency range from 500 to 550 megacycles.

power law, that is

$$I_g = K_2 \frac{E_g^{3/2}}{d_g}, \tag{2}$$

so that the grid power will increase as the fourth power of the grid diameter while the grid area and hence the heat dissipating ability only increases as the first power of the diameter. Because of this an upper limit in output exists, fixed by the maximum permissible heat dissipation per unit area for the grid structure. The optimum grid diameter will vary directly with the wave-length for which the tube is designed, and if the ratio of the grid length to its diameter is maintained constant, the maximum available power output (assuming the same efficiency) will vary as the square of the desired wave-length.

Circuit of a Positive Grid Oscillator

In Fig. 20 is shown a diagram of a positive grid tube of the straight-wire-grid type and its associated circuit. Tuned circuits, in this case in the form of so-called Lecher systems, are connected between the grid and plate leads, extending approximately a half wave-length (30 cm) beyond the lead seals. Because of the existence of preferred

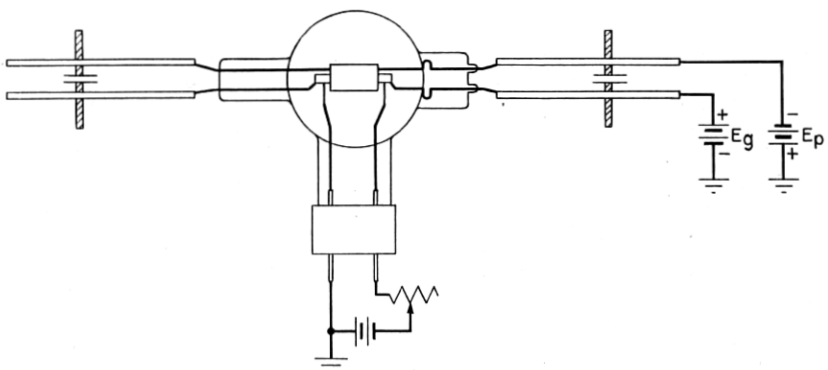


Fig. 20—A typical positive grid oscillator circuit.

frequencies of operation fixed by the potentials applied to the tube electrodes, distributed-constant circuits, if used, may be operated at frequencies corresponding to harmonic modes of oscillation. In this case the length of the leads within the tube envelope has been adjusted so that the glass seals come at or near potential nodal points for the Lecher systems of which the leads form a part. This minimizes dielectric losses in the glass. The effective paralleling of the two sets of leads greatly reduces the resistance losses, while the balanced arrangement decreases radiation losses. Strict attention to these details is required because of the already low efficiency of the mechanism of generation.

Characteristics of Positive Grid Oscillators

The dependence of output and anode efficiency on frequency is shown in Fig. 21. These data were taken by adjusting the circuit tuning, filament current, and the grid and plate potentials to their optimum values for each frequency. The curve showing the grid voltage will be observed to follow equation (1) above, at least roughly, and a similar correspondence will be observed between the curve for

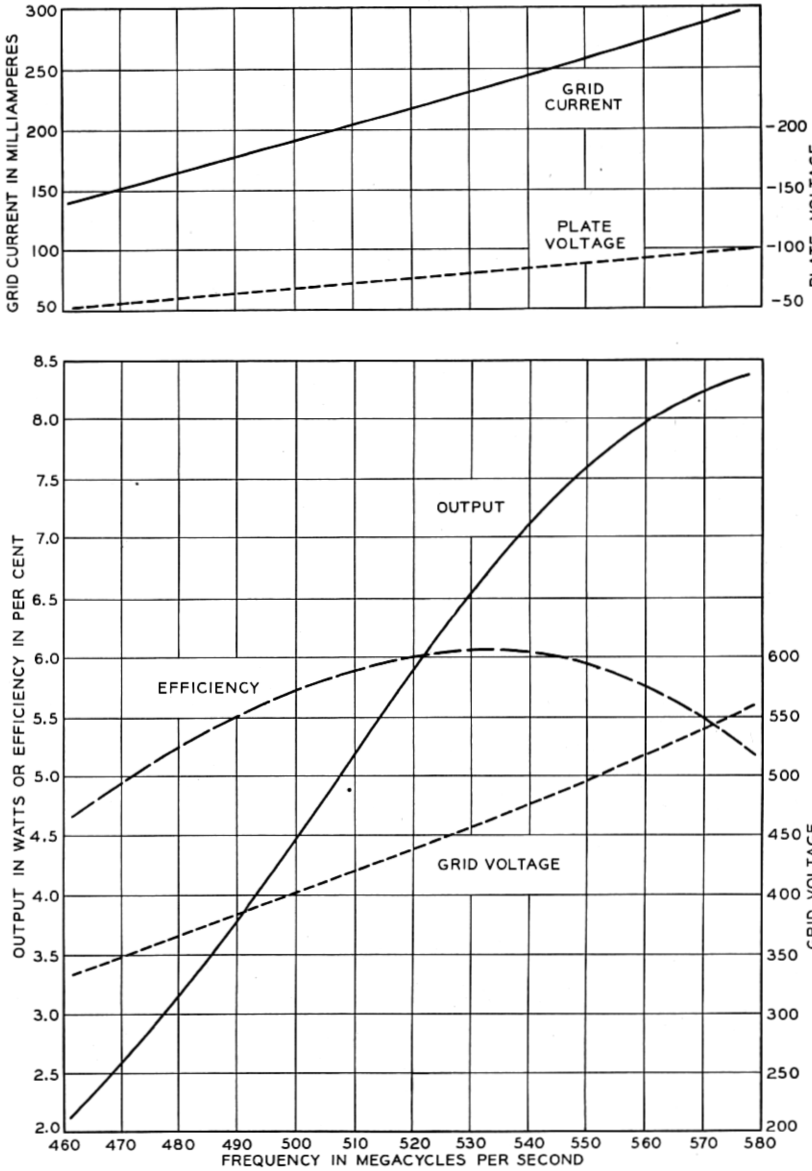


Fig. 21—Output and efficiency curves for the tube shown in Fig. 19.

the grid current and equation (2). Some variation in the required negative plate potential is observed. A maximum efficiency will be noted at a frequency of approximately 530 megacycles. The output, however, continues to increase with increasing frequency, the limit in output as well as in frequency being set by the safe grid dissipation. The outputs over the 500- to 600-megacycle range vary from 4.5 to 8 watts, comparing with outputs from 6 to 3 watts for the negative grid tube. The low efficiencies of 5 to 6 per cent are to be compared with the somewhat higher efficiencies of 19 to 11 per cent for the negative grid type tube.

The influence of the grid voltage on the frequency and on the output and efficiency is shown by the curves in Fig. 22. These data are for a

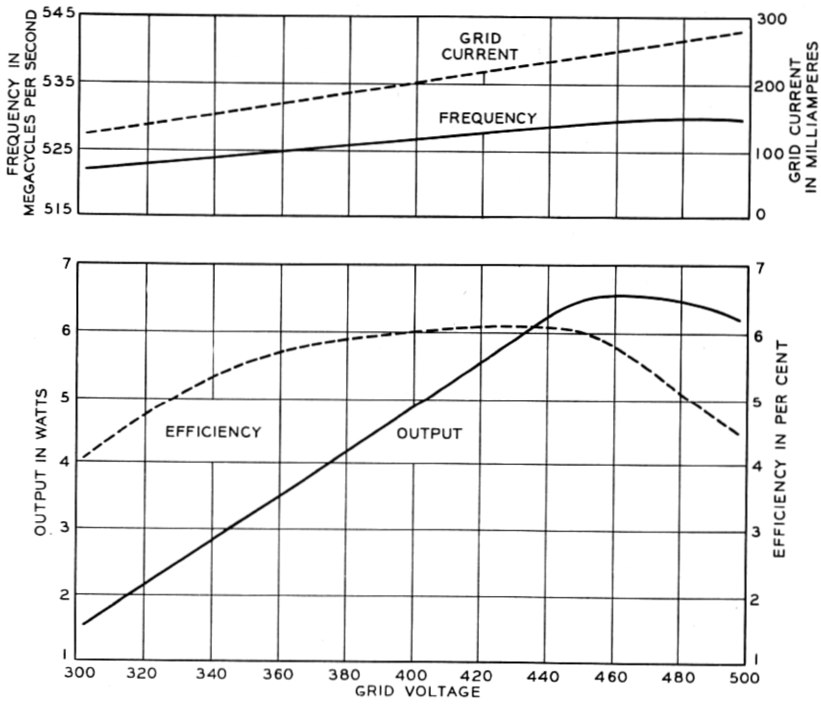


Fig. 22—Result of variation of grid voltage, tuning fixed, on tube of Fig. 19.

fixed circuit tuning, the grid voltage being adjusted to the values indicated. This corresponds to the condition that might obtain if a grid voltage modulation scheme were to be used. The lack of linearity of the output curve and the large shift in frequency indicate that amplitude modulation by this method would be unsatisfactory. The frequency shift, large as it is, is much less than the shift observed in tubes of poorer design and correspondingly lower efficiency.

The dependence of the output and efficiency as well as frequency upon the grid current is shown in Fig. 23. These data were taken with

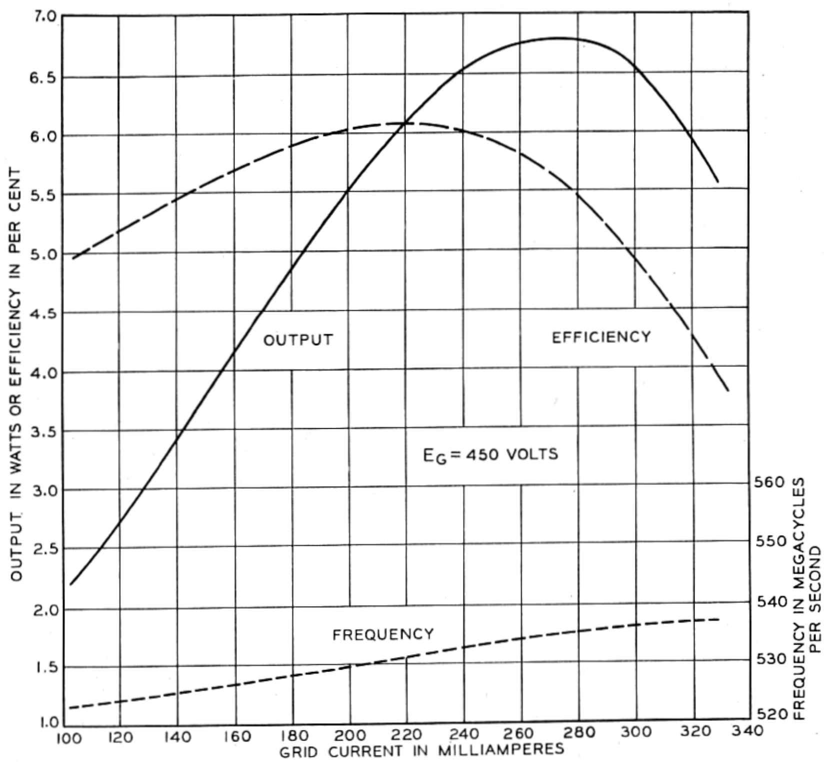


Fig. 23—Result of variation of grid current, other adjustments fixed, on tube of Fig. 19. $f = 532$ megacycles.

a grid potential of 450 volts and a fixed circuit adjustment corresponding roughly to a frequency of 532 megacycles. The current to the grid was varied by adjusting the temperature of the filament. The maxima observed in both the output and the efficiency correspond to conditions for which the grid current is limited primarily by the available emission rather than by space charge. As conditions corresponding to complete space charge are approached the output and efficiency fall off rapidly. The limit on the permissible grid dissipation prevents the extension of these curves to the condition of complete space charge. Because of this dependence of output on grid current, the adjustment of filament temperature is extremely critical.

At lower frequencies the efficiency of operation of a correctly designed positive grid tube is substantially the same as that exhibited by this tube. The negative grid oscillator on the other hand, as has been shown, increases both its output and efficiency rapidly with decreasing frequency. The positive grid oscillator is, therefore, at an increasing disadvantage at lower frequencies. With the present state of development, the negative grid oscillator will give larger outputs with higher anode efficiencies at all frequencies less than about 300 megacycles.

For frequencies much higher than 600 megacycles, it is found that the power input requirements for efficient operation of tubes having grids of the straight wire type are in excess of that which can be tolerated in the grid structures. Operation at very much less than optimum input results in considerable decrease in output as indicated in Fig. 25.

Spiral Grid Barkhausen Tubes

If the grid of a Barkhausen oscillator is in the form of a simple helix, oscillations at frequencies greater than those predicted by the relationship of equation (1) are readily obtained. When so constructed they are called spiral grid Barkhausen tubes. Some experimental models are shown in Fig. 24. The tubes used in the Lympne to St.

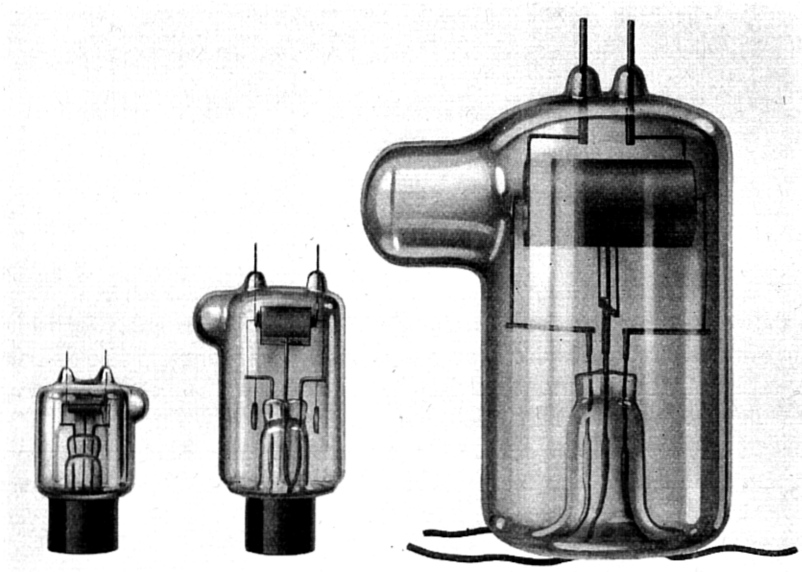


Fig. 24—Three optimum positive grid oscillators of the spiral grid type. Smallest tube designed for 2500 megacycles, largest for 500 megacycles.

Inglevert "micro-ray link" are of this general type.[14] Such tubes have been used to produce oscillations up to 3000 megacycles.

Because of the fact that the severe limitation on the optimum grid diameter is modified by the presence of a tuned circuit within the tube formed by the helical grid helix, tubes of this type are particularly useful at frequencies above 600 megacycles. The former restriction on grid diameter is replaced by the requirement that the expanded length of the grid spiral be approximately 1.24 times the wave-length at which the maximum output is required, and that there be a correct proportioning of the other dimensions of the tube. The dependence of wave-length on the grid wire length is illustrated by the experimental data in Table I covering a frequency range from 460 megacycles

TABLE I

DEPENDENCE OF WAVE-LENGTH ON GRID WIRE LENGTH FOR BARKHAUSEN OSCILLATOR WITH HELICAL GRID

Grid Wire Length in Cm.	Optimum Wave-length in Cm.	Ratio
16.3	13.5	1.21
18.6	18.6	1.00
19.7	14.5	1.36
20.4	18.0	1.13
21.4	17.5	1.22
21.3	25.0	0.85
22.3	20.2	1.10
25.2	18.6	1.35
30.6	25.0	1.22
32.0	23.6	1.36
32.0	25.5	1.25
33.4	25.0	1.33
42.6	29.0	1.47
42.6	29.5	1.44
42.6	30.2	1.41
42.6	30.7	1.38
53.2	43.5	1.22
80.0	65.0	1.23
Average		1.24

to 2220 megacycles. Graphic evidence of the independence of shape is shown by the largest and the smallest tube shown in Fig. 24 for which the dimensional ratios are nearly the same. The largest tube delivers several watts at 500 megacycles, while the smallest one delivers only a few tenths of a watt at 2500 megacycles. The efficiency in both cases is about one per cent. These dimensional considerations lead to the conclusion that there exists a maximum output at any given wave-length for a tube of a given design and that this output is proportional to the square of the optimum wave-length. From this it appears that the only advantage offered by the spiral grid tube over the other type is the simplification in mechanical design which permits the construction of rigid grid structures capable of high energy dissipation for the higher frequency range.

The external tuned circuit for the higher frequency mode of oscillation takes the form of a Lecher system connected between the two grid terminals. When so connected the dependence of frequency upon circuit tuning is pronounced, as contrasted with the negligible dependence observed if the Lecher system is connected between the plate and the grid. When oscillating in the higher-frequency mode the spiral grid tube shows only a comparatively small dependence of frequency on grid potential and this may be compensated by a proportional change in plate potential. This, coupled with the fact that the output increases rapidly with increasing grid potential, makes it possible to apply various schemes of amplitude modulation. Characteristics of the type shown in Figs. 21, 22, and 23 for the straight-wire-grid tube cannot be taken except for a limited portion of the range due to the inability of the grid to dissipate the energy required in the upper portion of the grid voltage or grid current ranges.

While the spiral grid tube will also oscillate in the lower-frequency mode, its efficiency and output are considerably lower than the corresponding values for the straight-wire-grid tube previously discussed. Its field of usefulness is, therefore, largely limited to the higher frequency mode of oscillation in the frequency range above 600 megacycles.

THE "MAGNETRON" OSCILLATOR

The "magnetron" in its simplest form consists of a cylindrical diode or 2-electrode tube, with a uniform magnetic field in the direction of the electrode axis. The original type of tube has been largely superseded for ultra-high-frequency generation by the so-called split-plate magnetron, first used by Okabe,[18] in which the cylindrical anode is divided longitudinally into two (or more) segments to the terminals of which is connected the tuned circuit. Such a tube is shown in Fig. 25.

In the frequency range from 300 to 600 megacycles the split-plate magnetron compares favorably with the negative grid tube both in output and in anode efficiency. Its use has been limited because of the complicating factor of the magnetic field, and the attending modulation difficulties. For frequencies higher than 600 megacycles the magnetron provides larger outputs than those so far reported by other means. It has been used at frequencies up to 30,000 megacycles, a value well above that so far reported for any other type of vacuum tube.

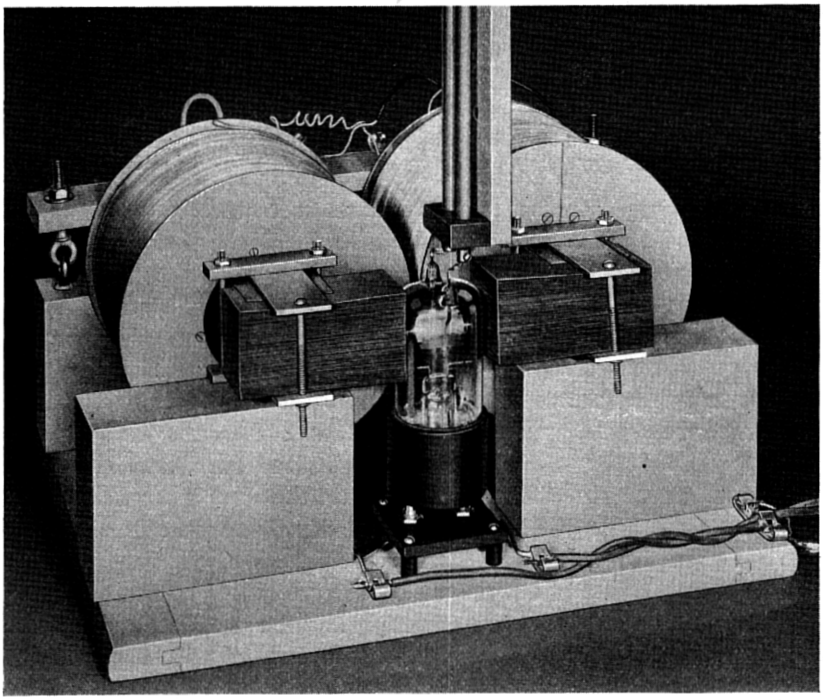


Fig. 25—An experimental model of the split-plate magnetron showing a possible arrangement of the magnetic field.

The magnetron depends for its operation upon the curvature of the electron orbits produced by the magnetic field. As first shown by Hull [15] in 1921, a critical field exists beyond which the anode current falls off rapidly to zero. This field is given by the relationship

$$H = \frac{6.72}{R}\sqrt{V}, \tag{3}$$

where R is the anode radius and V is the potential of the cylindrical anode with respect to an axial filament. Although the original magnetron of Hull and Elder made use of variations in the magnetic field in its operation as a generator, it was soon discovered that oscillators could also be produced with steady fields by two somewhat different mechanisms. The one, first pointed out by Habann,[16] makes use of a negative resistance effect observable in the static characteristics and the other, first described by Žáček,[17] involves the electron transit time in a way quite analogous to the way in which it is involved in the positive grid triode. Both mechanisms have been used to produce oscillations at ultra-high frequencies.

Negative Resistance Type

Data reported by McArthur and Spitzer [1] on a split-plate magnetron tube are illustrative of the negative resistance type of behavior. Static characteristics taken by varying the potential of one anode with the magnetic field held constant for different values of the potential on the other anode are shown in Fig. 26. The pronounced negative

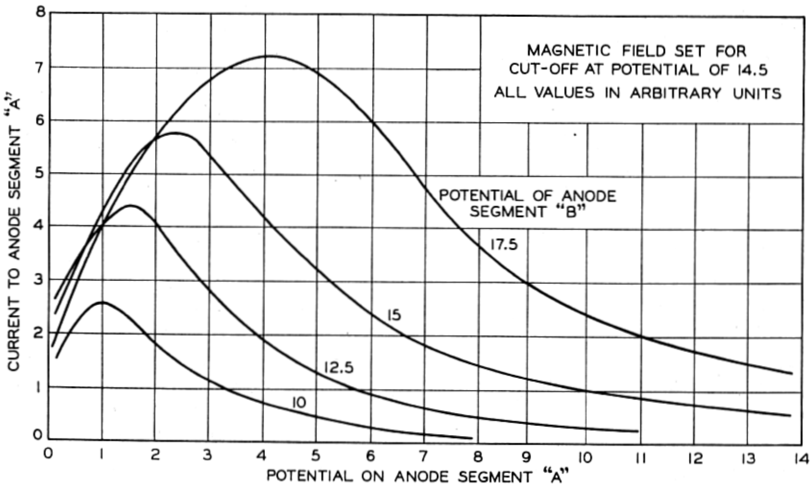


Fig. 26—Static characteristics of a split-plate magnetron.

resistance effect is obvious. This negative resistance characteristic can be utilized in producing oscillations.

Output and efficiency curves for this tube as an oscillator are shown in Fig. 27. These data were obtained by connecting a "tank"

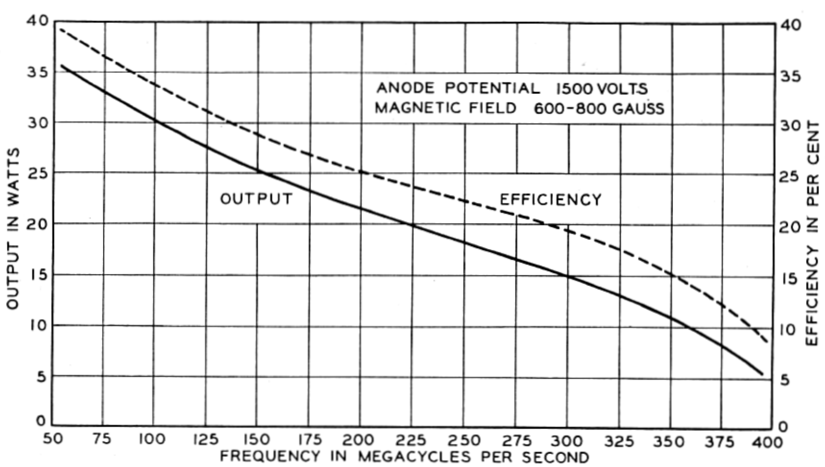


Fig. 27—Output and efficiency curves at different frequencies for split-plate magnetron.

circuit, tuned to the desired frequency, across the two anodes, as shown in Fig. 28. Each anode delivers energy to the oscillating circuit during alternate half-cycles, so that in effect, it is equivalent to a push-pull oscillator. The limiting frequency as set by the inter-electrode capacitances and lead inductances (corresponding to the similar limit for the negative grid tube) is 450 megacycles. The de-

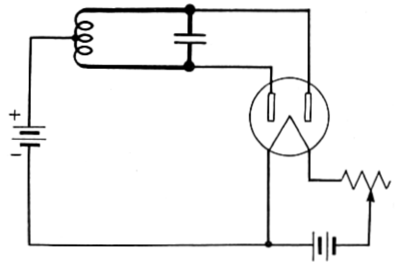


Fig. 28—Oscillation circuit of split-plate magnetron. Data for Fig. 27 taken in this type of circuit.

crease in output before this limit is reached is due to resistance and radiation losses and to the effect of electron transit time.

The magnetron, as contrasted with the negative grid tube, will oscillate with circuits having a high decrement. However, for its most efficient operation the effective anti-resonant impedance of the tuned circuit when loaded must be approximately 10 times the value required by a triode with the same anode dimensions. The load resistance that can be obtained at high frequencies is only a fraction of this value, so that the efficiency becomes increasingly less with higher frequencies. A further limitation is due to the fact that the electron current is concentrated on only a small part of the anode surface. This reduces the safe anode dissipation unless the anode is designed to have a high thermal conductivity. Because of these limitations, the ratio of output to the inter-electrode capacitance may be only slightly more favorable than the corresponding ratio for a triode of the same anode dimensions.

Type Depending on Electron Transit Time

When the magnetic field of a split-plate magnetron is adjusted to near the critical value given by equation (3), oscillations can be produced whose frequency will depend primarily upon the time of flight of electrons between filament and anode in a way closely resembling the behavior of the positive grid oscillator in its lower frequency mode of oscillation. For best output, the field must be above the critical value. To fix the time of flight and hence the frequency of oscillation, the magnetic field and plate voltage must be adjusted to certain values roughly expressed by the empirical relationship

$$\lambda H = 13{,}100, \tag{4}$$

where λ is the wave-length in centimeters and H is the field strength in gausses, which must also satisfy equation (3). It is found that for best operation the magnetic and electric fields within the tube should not be exactly perpendicular. This lack of perpendicularity may be achieved either by tipping the magnetic field relative to the tube axis or by introducing end plates within the tube and maintaining them at a fixed positive potential.

Kilgore [19] has given complete information concerning this type of oscillator. In Fig. 29, taken from his paper, is shown the dependence

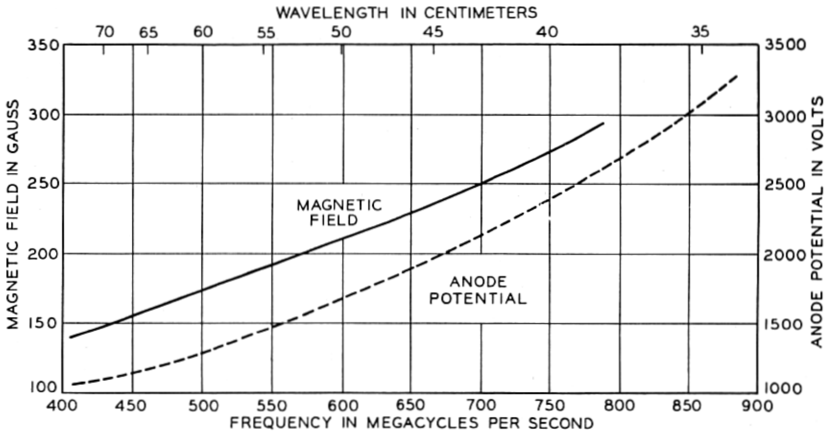


Fig. 29—Relation of magnetic field and anode potential to frequency of oscillation in magnetron oscillator of second type.

of field strength and anode potential on the desired frequency. The existence of a preferred frequency fixed by these values is confirmed by the data in Fig. 30 relating the output and wave-length with the length of the attached Lecher system. The decreased output shown at the second peak is due to the added losses introduced by the extended length of the system. The outputs shown on these curves are not in watts, but represent relative readings of the field strength near the oscillator. With optimum adjustments 7 watts at 715 megacycles is reported, the efficiency being about 8 per cent. The dependence of output and frequency on the applied anode potential

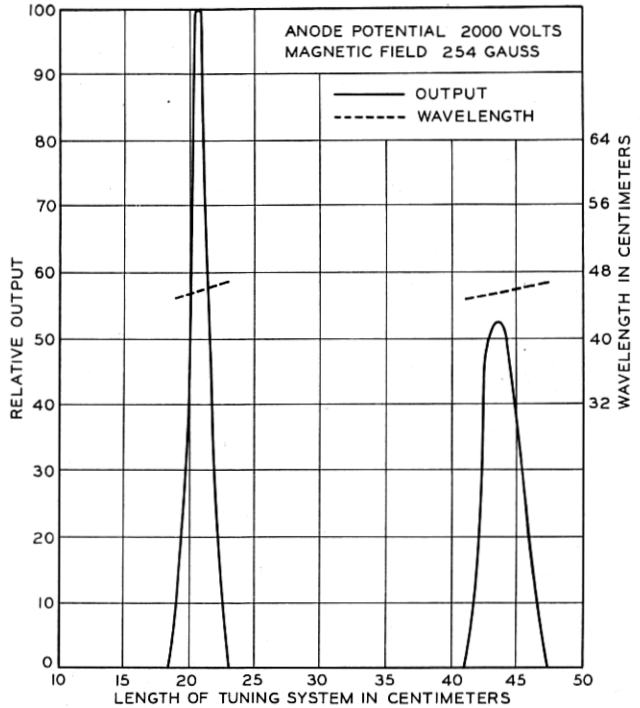


Fig. 30—Relation of wave-length and output to length of tuning system in magnetron oscillator of second type. Anode potential—2000 volts, Magnetic field—254 gausses.

is shown in Fig. 31, and the dependence of frequency on the current in the magnetic field coil in Fig. 32. The importance of the adjustment of the field angle is shown by the data in Fig. 33.

An output of 2.5 watts at 3160 megacycles has been reported by Wolff, Linder, and Braden.[22] They find that the efficiency of the tube is much improved by using end plates in place of the tipped magnetic field. Cleeton and Williams [21] have been able to obtain oscillations at 30,000 megacycles with a magnetron tube.

Amplification

The use of the conventional thermionic triode as an amplifier greatly exceeds its use as an oscillation generator in communication applications. Its ability to amplify has contributed much more to the development of our present-day long distance communication, whether by wire or by radio, than has its ability to oscillate. The complete utilization of ultra-high frequencies as carrier channels in communica-

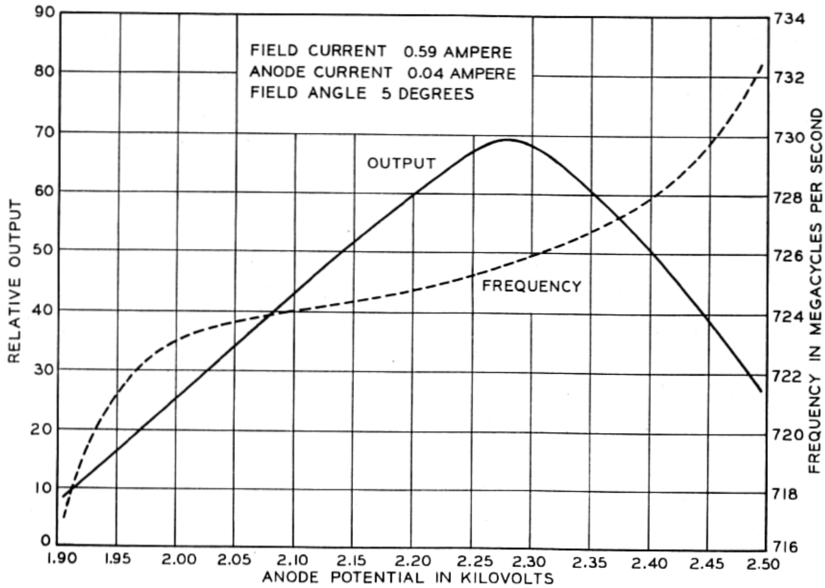


Fig. 31—Relation of output and frequency to anode potential in magnetron oscillator of second type.

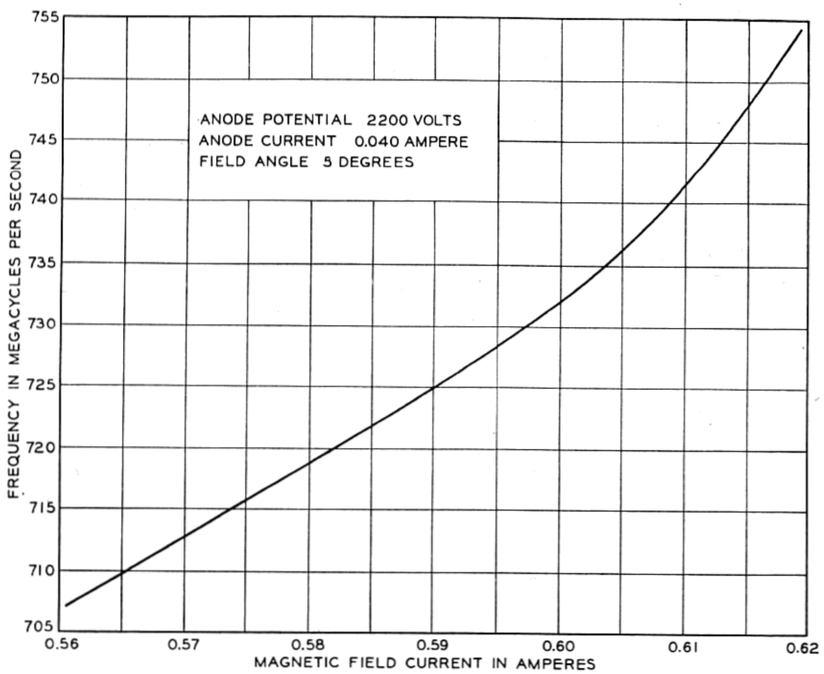


Fig. 32—Relation of frequency to magnetic field current in magnetron oscillator of second type.

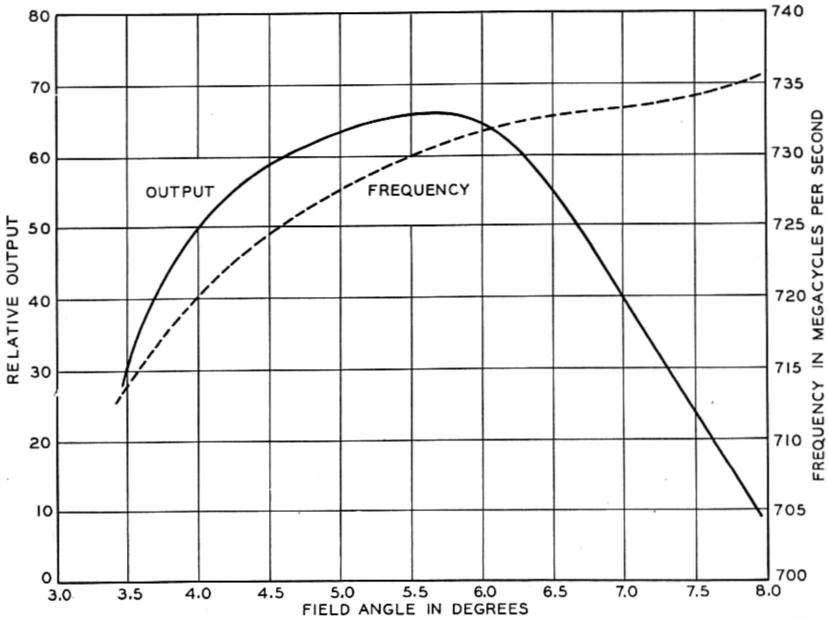


Fig. 33—Relation of output and frequency to field angle in magnetron oscillator of second type.

tion will also, no doubt, be dependent upon the development of suitable amplifiers for this frequency range. Although certain forms of pseudo-amplification are possible with tubes of the Barkhausen and magnetron types, the negative grid triode and multi-element tubes derived therefrom are the only devices available for very high frequencies which will amplify in the sense that the output is an enlarged undistorted replica of the input.

As the frequency of operation of the negative grid triode is increased, difficulties in securing stable operation as an amplifier and in realizing the full gain indicated by the tube constants are encountered. These difficulties, as is well known, are in the main due to the tendency of the amplifier to oscillate or "sing" because of feed-back through the grid-plate capacitance. This may be overcome either by the introduction of a compensating capacitance somewhere in the circuit, so-called neutralization, or by the introduction of an electrostatic shield or screen within the tube envelope between the grid and plate, giving the screen-grid tetrode. Neutralization schemes fail at very high frequencies because of the inductance of the tube leads which makes difficult the correct location of the neutralizing capacity and because of transit-time effects which shift the phase of the needed compensation. However, conventional screen-grid tetrodes and pentodes are available which function satisfactorily over the major portion of the frequency range covered by the conventional 3-element tube as an oscillator.

For frequencies above approximately 60 megacycles specially designed tubes are required. Because of the similarity in the special frequency requirements, it is expected that there will be found a succession of multi-element tubes for amplification use, each rated for a band of frequencies, patterned after corresponding triode oscillators. The special frequency requirements for the amplifying tube are even more severe than those for the triode oscillator, so that the multi-element amplifying tube will in general cease amplifying at a frequency somewhat lower than the frequency limit of oscillation of the corresponding triode oscillator.

Thompson and Rose [3] have described small screen-grid tubes which will amplify at frequencies of 300 to 400 megacycles. One of these tubes is shown in Fig. 13. Their characteristics are similar to those of the conventional screen-grid tube in many respects. The very great reductions in inter-electrode capacitances, lead inductances, and transit time make possible the construction of receiving circuits using tuned radio frequency amplification at these very high frequencies. The ratio of the frequency limits of the corresponding triode as an oscillator (1000 megacycles) to the frequency at which amplification was reported (400 megacycles) is typical and illustrates the apparently inevitable failure of the amplifier to keep pace with the oscillator in the struggle toward higher and higher frequencies.

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