PART II

MAGNETRON OSCILLATORS FOR THE GENERATION OF FREQUENCIES BETWEEN 300 AND 600 MEGACYCLES*

BY

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Summary—*The need for vacuum tube generators capable of delivering appreciable power at frequencies from 300 to 600 megacycles is pointed out and the negative resistance magnetron is suggested as one of the more promising generators for this purpose.*

An explanation of the negative resistance characteristic in a split-anode magnetron is given by means of a special tube which makes possible the visual study of electron paths. In this manner it is demonstrated how most of the electrons starting toward the higher potential plate reach the lower potential plate.

From the static characteristics it is shown how the output, efficiency, and load resistance can be calculated, and from this analysis it is concluded that the negative resistance magnetron is essentially a high efficiency device at low frequencies.

Measurements of efficiency at ultra-high frequencies are given for several magnetrons under various operating conditions. It is concluded from these measurements that the decrease of efficiency at very high frequencies is mainly due to electron-transit-time effects. A general curve is given showing efficiency as a function of the "transit-time ratio." This curve indicates that for a transit time of one-fifteenth of a period, approximately fifty per cent efficiency is possible; for one-tenth of a period, thirty per cent; and for one-fifth of a period, the efficiency is essentially zero.

Two methods are described for increasing the plate-dissipation limit. One method is that of increasing the effective heat-dissipating area by the use of an internal circuit of heavy conductors. The other method is that of a special water-cooling arrangement which also makes use of the internal circuit construction.

Examples of laboratory tubes are illustrated, including a radiation-cooled tube which will deliver fifty watts at 550 megacycles and a water-cooled tube which will deliver 100 watts at 600 megacycles.

I. INTRODUCTION

THE demand for more ultra-high-frequency channels has necessitated the development of generators for frequencies of higher and higher order. This development has progressed in two directions; the extention of the upper frequency limit of conventional oscillators and amplifiers, and the investigation of other types of generators

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especially adapted to ultra-high frequencies, such as Barkhausen-Kurz oscillators,[1] and magnetron oscillators.

A review of the work done shows a tendency to concentrate on the second line of development with an emphasis on obtaining the very highest frequencies rather than on obtaining appreciable power at frequencies just above the limit of conventional tubes. As a result little work has been done until very recently towards the generation of power at frequencies between 300 and 600 megacycles.

At the same time the advancement of the receiving tube art with the introduction of the "acorn" type tube[2,3] has made it possible to build practical receivers for frequencies somewhat above 300 megacycles. This fact brings nearer the practical utilization of these frequencies and makes it more important to obtain satisfactory generators.

While considerable progress has been made in extending the usefulness of the feed-back oscillator above 300 megacycles, the possibilities of other means of generation cannot be disregarded. One of the less conventional means which shows promise from the standpoint of output and efficiency is the magnetron oscillator.

Magnetron oscillators for generation of ultra-high frequencies can be classed as "electronic oscillators"[4,5,6,7,8,9] and "negative resistance" oscillators,[10] the former being of little importance in the frequency range under consideration. However, for the sake of clearness both types will be defined.

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[1] H. Barkhausen and K. Kurz, "Shortest Waves Obtainable With Valve Generators," *Phys. Zeit.*, Vol. 21, pp. 1-6; January (1920).

[2] B. J. Thompson and G. M. Rose, Jr., "Vacuum Tubes of Small Dimensions For Use at Extremely High Frequencies," *Proc. I.R.E.*, Vol. 21, pp. 1707-1721; December (1933). (See Page 334).

[3] B. Salzberg and D. G. Burnside, "Recent Developments in Miniature Tubes," *Proc. I.R.E.*, Vol. 23, pp. 1142-1157; October (1935).

[4] This type of magnetron oscillator was first described in the literature by Zacek[5] in 1924, and was later discussed in papers by Okabe,[6] Yagi,[7] Kilgore,[8] Megaw,[9] and others. It is sometimes referred to as a "Magnetostatic oscillator."[8]

[5] A. Zacek, "A Method of Generating Short Electromagnetic Waves," *Casopis pro Pestovani Mathematiky a Fysiky* (Prague), Vol. 53, p. 378; June (1924); (summary in *Zeit. für Hochfrequenz.*, Vol. 32, p. 172, (1928).

[6] K. Okabe, "Ultra-Short Waves from Magnetrons," *Jour. I.E.E.* (Japan), p. 575, June (1927).

[7] H. Yagi, "Beam Transmission of Ultra-Short Waves," *Proc. I.R.E.*, Vol. 16, pp. 715-740; June (1928).

[8] G. R. Kilgore, "Magnetostatic Oscillators for Generation of Ultra-Short Waves," *Proc. I.R.E.*, Vol. 20, pp. 1741-1751; November (1932).

[9] E. C. S. Megaw, "An Investigation of the Magnetron Short-Wave Oscillator," *Jour. I.E.E.* (London), Vol. 72, pp. 326-348; April (1933).

[10] Otherwise referred to as a "dynatron magnetron"[9] and as a "Habann generator."

An *electronic magnetron* oscillator can be defined as one which operates by reason of electron-transit-time phenomena and in which the frequency is essentially determined by the electron-transit time. Although this type of oscillator is capable of generating the very highest frequencies obtainable with vacuum tubes, it has an inherently low efficiency (approximately ten per cent) and a very limited output. At frequencies between 300 and 600 megacycles, the possible output is much smaller than that obtainable from the negative resistance magnetron.

A *negative resistance* magnetron oscillator is defined as one which operates by reason of a static negative resistance between its electrodes and in which the frequency is equal to the natural frequency of the circuit. In its usual form it consists of a cylindrical plate and coaxial filament, the plate being split into two or more segments. Both the two-segment and the four-segment[11,12,13,14] form are being used with success, but in this paper the discussion will be limited to the two-segment type.

The basic idea of the negative resistance magnetron was disclosed by Habann[15] in 1924. Since that time a number of papers on the subject have appeared; notably those of Spitzer and McArthur,[16] Megaw,[9] and Slutzkin[17] and his associates. Although the present paper necessarily covers some of the same ground as the previous papers, it represents an independent investigation of the subject by the writer in the past few years.

It is the object of this paper to discuss the two-segment negative resistance magnetron with regard to mechanism of oscillation, limitations in efficiency and power output at ultra-high frequencies, and its application to generation of large power output at frequencies from 300 to 600 megacycles.

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[11] The four-segment construction appears to have been first mentioned in the literature by Yagi[7] and later discussed by Posthumous,[12] Runge,[13] and others. Recently there has been considerable discussion as to whether the four-segment tube can be classed as a negative resistance oscillator.[14] The present writer feels that there is enough difference between the two-segment and four-segment tubes at ultra-high frequencies to warrant a separate treatment of the two types.

[12] K. Posthumous, "Oscillations in a Split-Anode Magnetron," *Wireless Engineer,* Vol. 12, pp. 126-132; March (1935).

[13] W. Runge, "Four-Segment Magnetron," *Telefunken Zeitung,* Vol. 15, p. 69; December (1934).

[14] E. C. S. Megaw and K. Posthumous, "Magnetron Oscillators," *Nature,* Vol. 135, p. 914; June 1 (1935).

[15] E. Habann, "A New Vacuum Tube Generator," *Zeit. für Hochfrequenz.,* Vol. 24, pp. 115-120; 135-141, (1924).

[16] E. D. McArthur and E. E. Spitzer, "Vacuum Tubes as Ultra-High Frequency Generators," *Proc. I.R.E.,* Vol. 19, pp. 1971-1982; November (1931).

[17] A. A. Slutzkin, "Theory of Split-Anode Magnetrons," *Phys. Zeit. der Sowietunion,* Vol. 6, pp. 280-292, (1934).

II. Theory of Negative Resistance Magnetron Oscillators

Before considering the negative resistance magnetron at ultra-high frequency it is well to study the fundamental principles underlying its operation.

The usual circuit of a split-anode magnetron oscillator is shown in Figure 1. Oscillations can be started by applying a magnetic field of proper magnitude parallel to the filament. The value of magnetic field required is somewhat beyond the "critical" value, which is defined as the field required to cause all of the electrons to miss the plate when both plate halves are at the same potential. The expression for the "critical field"[18] is

$$H_c = \frac{6.72}{R_a} \sqrt{E_0} \tag{1}$$

where,

R_a = anode radius in centimeters

H_c = critical field in gausses

E_0 = average plate potential in volts.

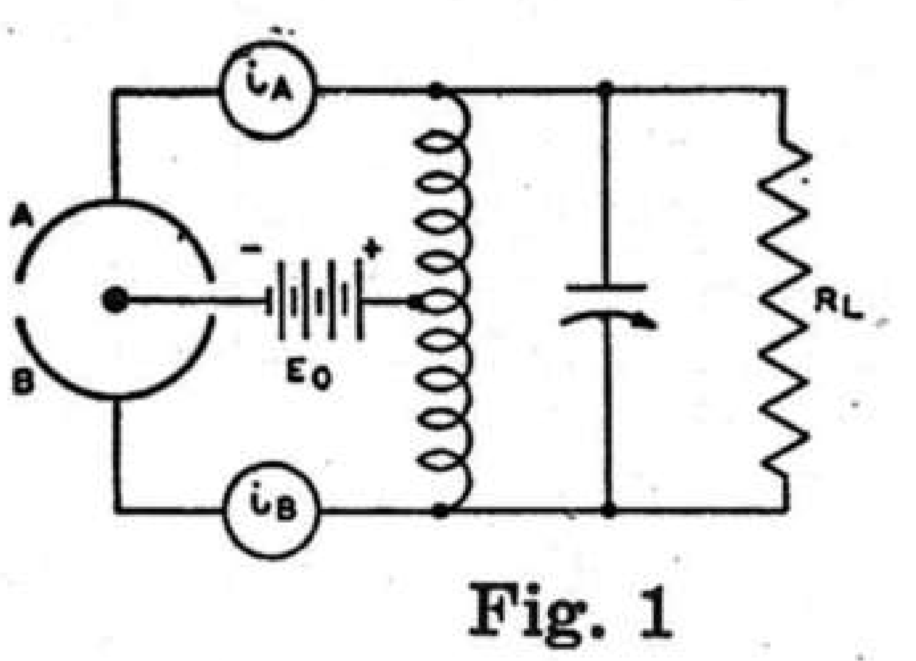

Fig. 1

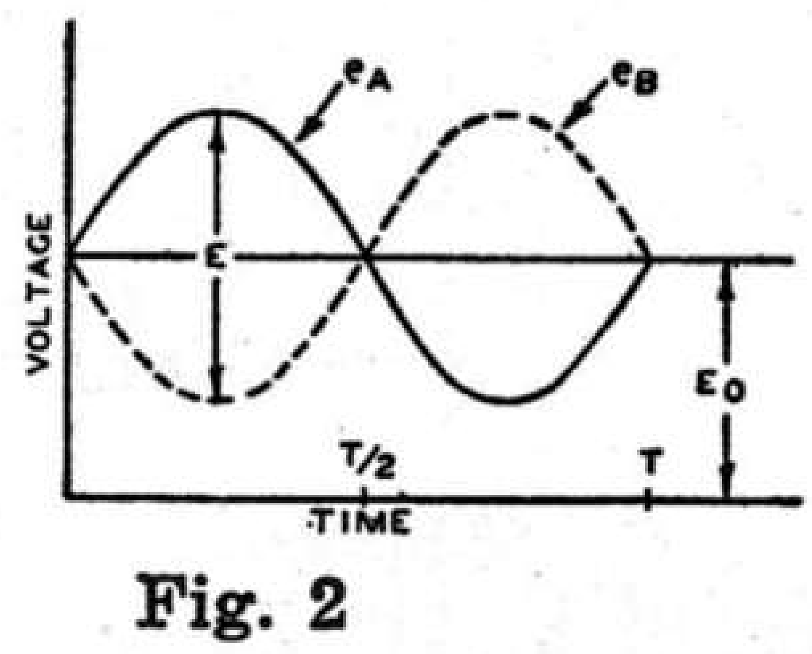

Fig. 2

Fig. 1—Two-segment magnetron oscillator circuit.

Fig. 2—Instantaneous potentials on the plate halves of a two-segment magnetron oscillator.

During the oscillation cycle, the instantaneous potentials on the plate halves can be represented as shown in Figure 2.

It is possible to demonstrate the reason for oscillation by referring to the volt-ampere characteristics, which can be shown in a number of ways. Probably the best method of representing these characteristics is illustrated in Figure 3. For this example, a tube having a 0.5-centimeter diameter plate was used and the curves were taken for the condition of 500 volts average plate potential and a magnetic field equal to approximately 1.5 times the "critical field."

The method of taking these characteristics was to increase the potential of plate *A* by increments and, at the same time, decrease the potential of plate *B* by the same increments, so as to simulate condi-

[18] A. W. Hull, "Effect of a Uniform Magnetic Field on the Motion of Electrons Between Coaxial Cylinders," *Phys. Rev.*, Vol. 18, pp. 31-57; September (1921).

tions during oscillation. When the currents to the plate segments are measured, it is found that more current flows to plate B than to plate A even though plate B is at the lower potential. Furthermore, as the potential difference $(E_A - E_B)$ is increased, up to a certain point, the excess of current to plate B increases. The current $(I_A - I_B)$ plotted against the potential $(E_A - E_B)$ gives the curve OPB of Figure 3, the portion OP of which represents a negative resistance across the circuit. This negative resistance is sufficient to account for self-sustained oscillations.

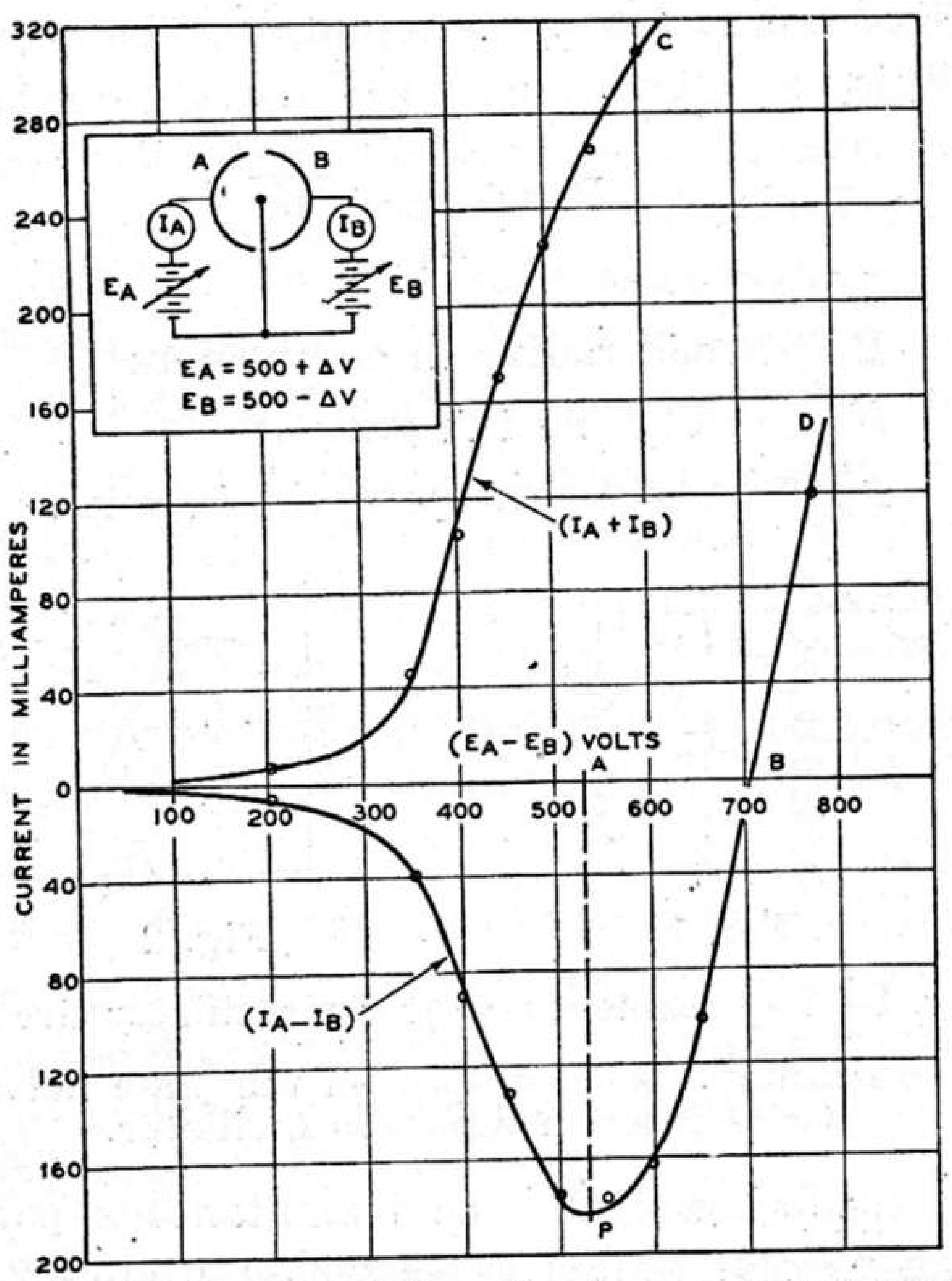

Fig. 3—Static characteristics of a two-segment magnetron.

To understand why such a characteristic should exist, it is necessary to study the electron paths under various potential conditions. With equal potentials on the plate halves, and with magnetic field beyond the "critical value," the electron paths are symmetrical curves of the type shown in Figure 4. However, when the plate halves are at different potentials, say $E_A = +150$ and $E_B = +50$, the paths are more complicated. An approximate idea of what an electron will do in this case can be had by studying an electrostatic-flux plot as shown in Figure 5. Consider first the case of an electron starting toward the high potential plate. The electron after passing the slot plane will enter a low potential region which *decreases the radius of curvature* and causes the electron to curve back somewhat short of the filament. This results in the electron describing one or more loops, finally landing on the lower potential plate in most cases as shown in Figure 5.

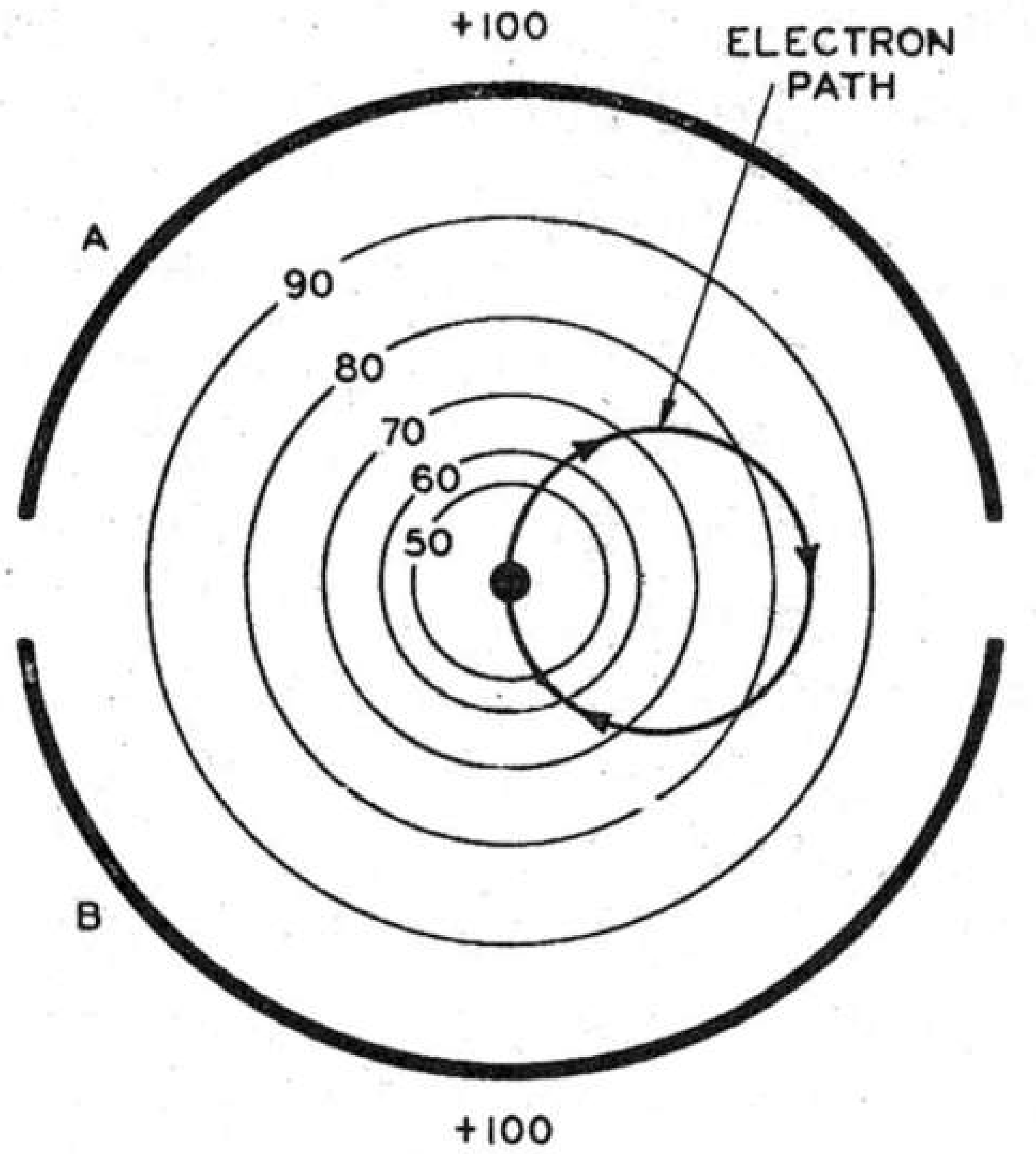

Fig. 4

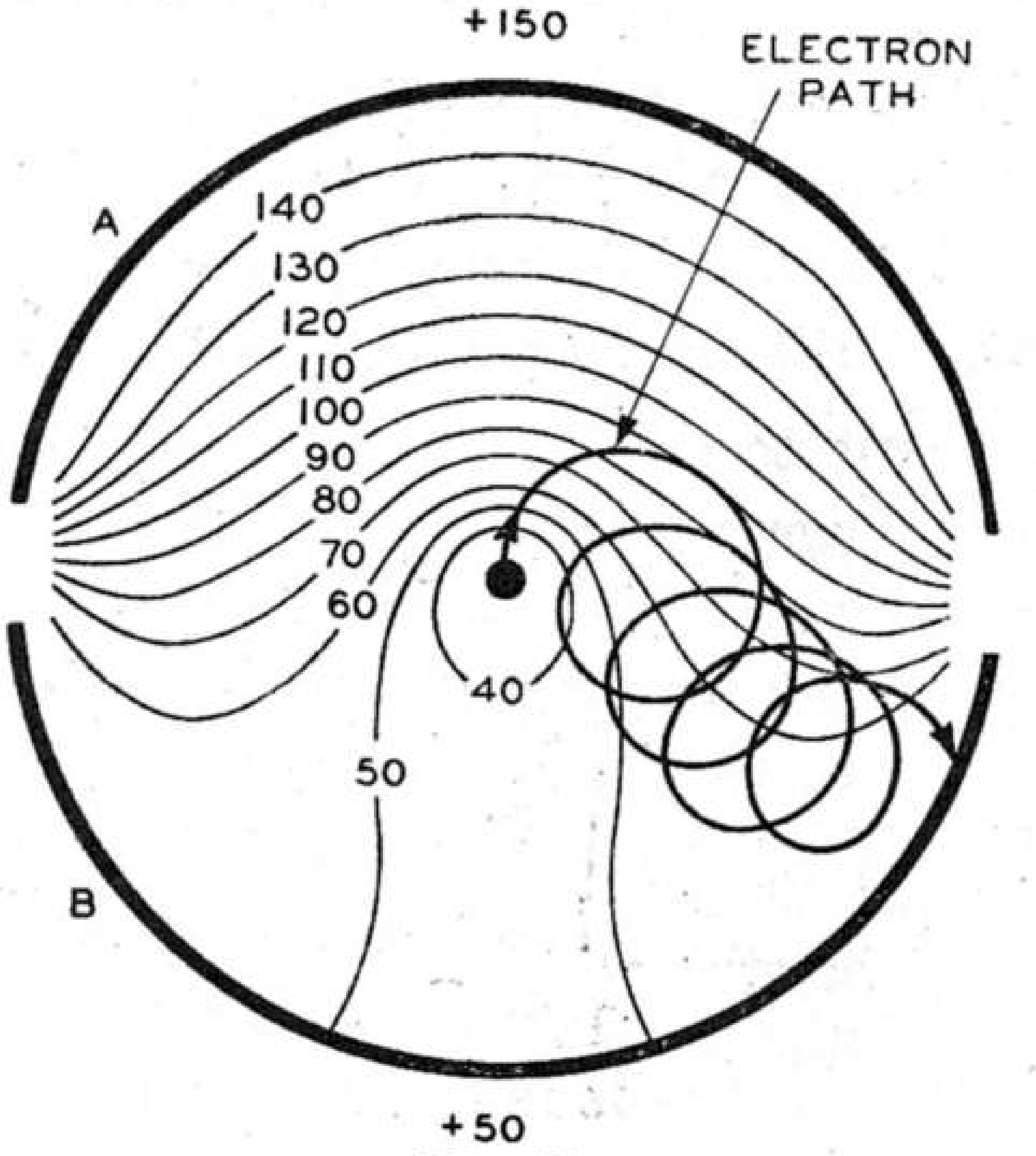

Fig. 5

Fig. 4—Electron path in a two-segment magnetron when the plate halves are at the same potential and the magnetic field is 1.5 times the critical value. (In Figs. 4, 5, and 6 the lightweight lines represent equipotential surfaces.)
Fig. 5—Electron path in a two-segment magnetron when the plate halves are at different potentials and the electron starts toward the higher potential plate. Magnetic field 1.5 times critical value.

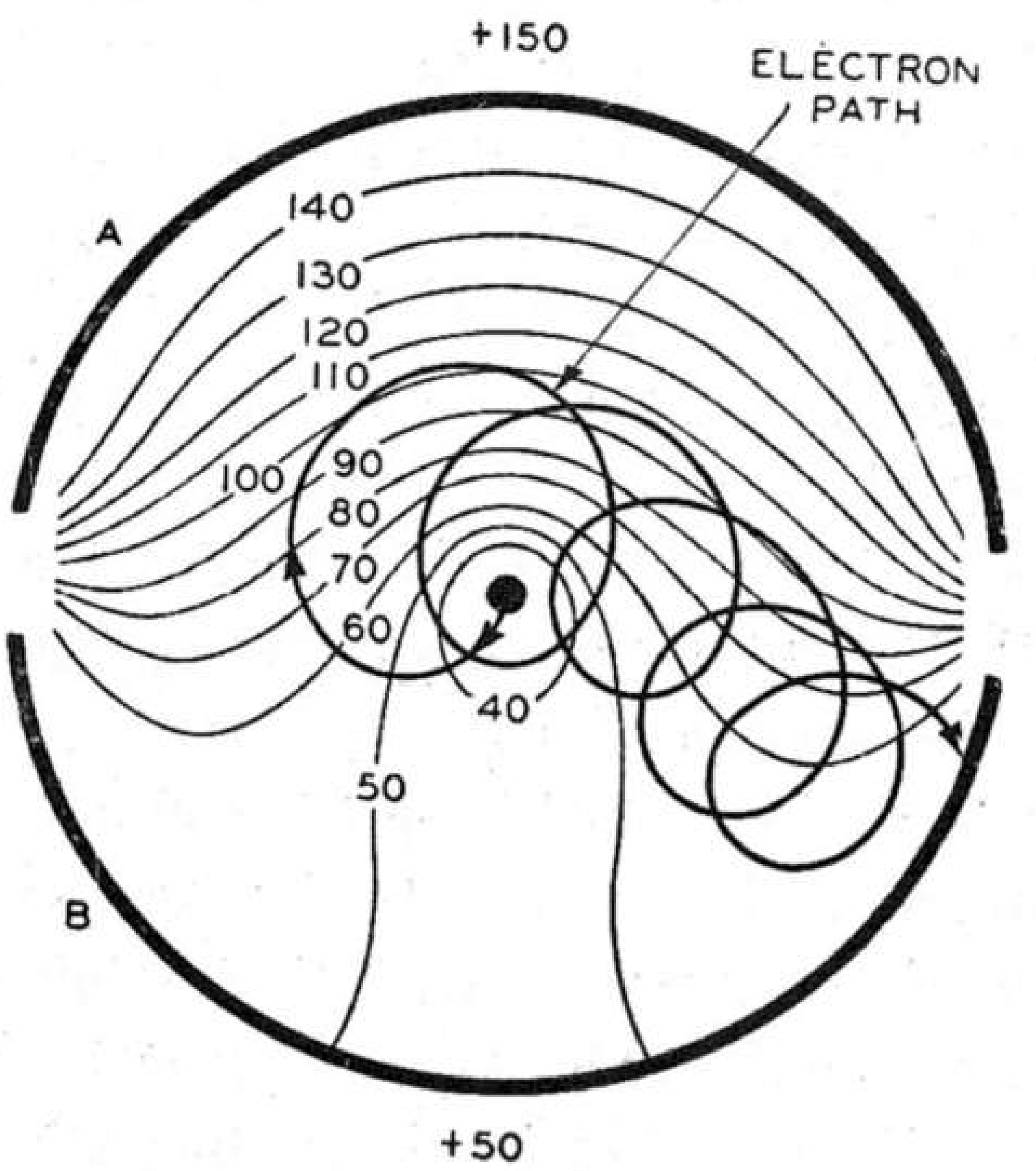

Fig. 6

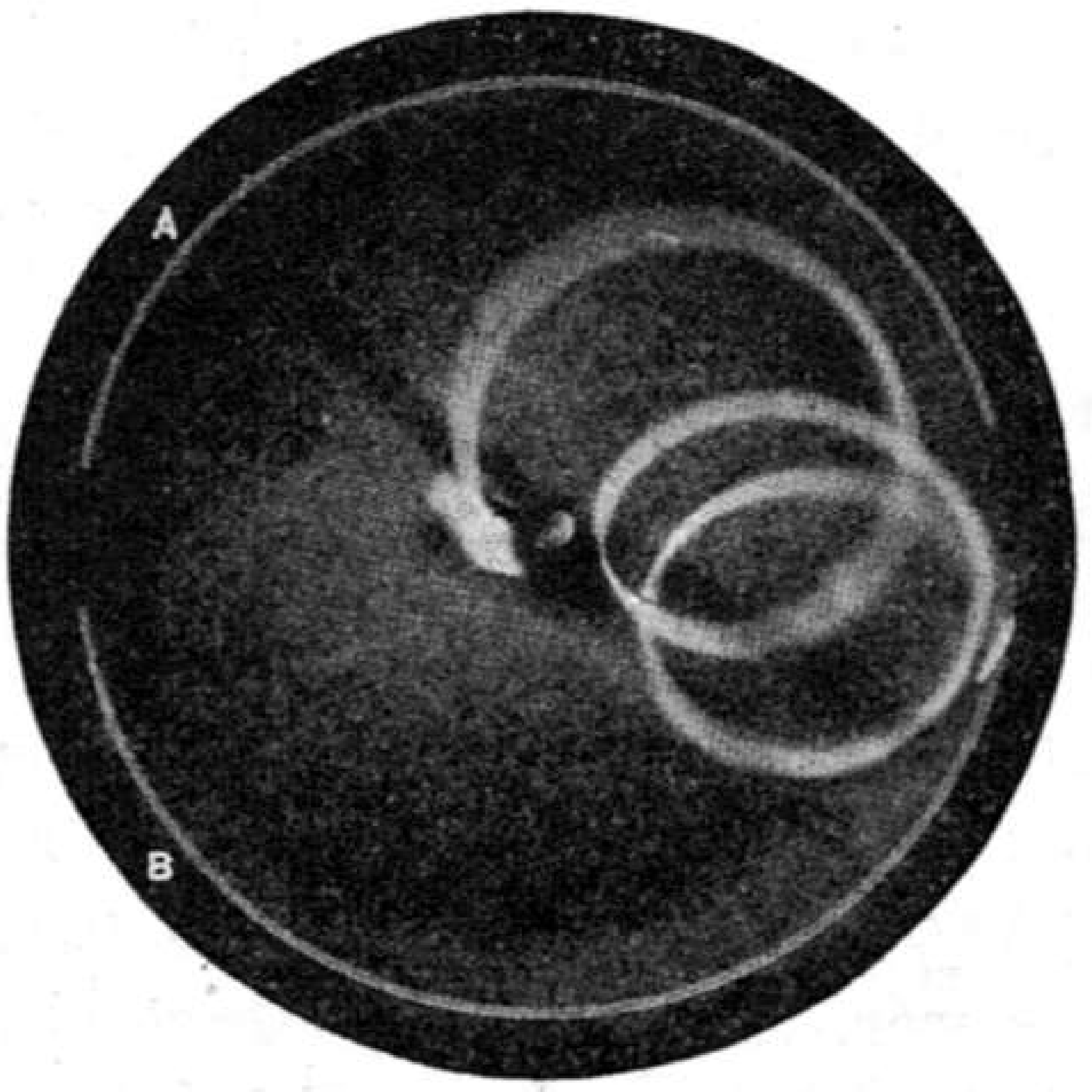

Fig. 7

Fig. 6—Path of an electron starting toward the lower potential plate. Magnetic field 1.5 times critical value.
Fig. 7—Photograph of ionized path of an electron stream starting toward the higher potential plate. Magnetic field 1.25 times critical. $E_A = +300$ volts, $E_B = +250$ volts.

On the other hand, the electrons which start toward the lower potential plate will pass the slot plane into a higher potential region with a resulting *increase in radius of curvature,* and a consequent encircling of the filament as shown in Figure 6. In this case, it is more difficult to say what the ultimate destination of the electrons will be, but it appears probable that these electrons will also eventually reach the lower potential plate.

For an experimental check of these predictions, a special magnetron was built which made possible a visual study of electron paths by gas ionization. The cathode was constructed with a small emitting spot and made rotatable so that the electrons starting in any direction could be studied. Argon gas of a few microns pressure was used, which made the electrons beam just visible without essentially changing the shape of the beam trace. The terminal spot of the beam was also made visible by coating the plate halves with willemite.

With this tube it was possible to illustrate beautifully the predicted paths of the type shown in Figures 5 and 6. In some cases of high magnetic field, as many as ten or more loops were observed. A typical photograph of an electron-beam trace is shown in Figure 7 for the condition of $E_A = +300$, $E_B = +250$, and magnetic field equal to about 1.25 times the critical value. A systematic study was made of the electron paths by varying the direction of emission, the ratio of plate potentials, and the strength of magnetic field. The conclusion drawn from these observations is that, for sufficiently high magnetic field (one and one-half to two times critical) and with the ratio of E_A to E_B not too high (less than four to one), most of the electrons arrive at the lower potential plate no matter in what direction they started.

However, this fact in itself is not sufficient to explain fully the negative resistance characteristic. In addition, the space-charge effects must be considered. A complete analysis of the space-charge conditions in a magnetron is too involved to be attempted here, but a qualitative picture can be given as follows: With the magnetic field beyond the critical value and the plate halves at the same potential, no electrons will reach either plate; but as soon as E_A is increased by an increment and E_B decreased by the same increment, some electrons will flow to plate B as illustrated above. Because of the space-charge limitation, however, the number of these electrons will be only a small fraction of the total number emitted from the filament. It is clear that the space charge for a given current will be much higher than without magnetic field because the electrons describe several orbits before reaching the plate, thus contributing more to the space charge. Now a study of the electron paths shows that an increase in $(E_A - E_B)$ causes the electrons to describe fewer orbits. Therefore, an increase in $(E_A - E_B)$ will result in a smaller space charge and a, consequently, greater current to B.

This analysis is sufficient to explain the negative resistance characteristic such as is represented by the portion *OP* of the $(I_A - I_B)$ curve in Figure 3. The other part of the curve, *PBD*, can be explained by the fact that, as the ratio of E_A to E_B is increased, electrons eventually begin to arrive at plate *A* until, ultimately, more electrons are arriving at *A* than at *B*.

III. Calculation of Performance from the Volt-Ampere Characteristics

Having explained the reason for the typical volt-ampere characteristics in a split-anode magnetron it is interesting next to use these characteristics to calculate the oscillator performance. In this analysis, it is assumed that the transit time is very small compared to a period. Referring to the notation of Figures 1 and 2, and letting $e_A = E_0 + E/2 \sin \omega t$ and $e_B = E_0 - E/2 \sin \omega t$, it is easy to derive the following expressions:

$$\text{Plate Loss} = \frac{1}{T} \int_0^T e_A i_A dt + \int_0^T e_B i_B dt$$

$$= \frac{E_0}{T} \int_0^T (i_A + i_B)\, \mathrm{dt} + \frac{E}{2T} \int_0^T (i_A - i_B) \sin \omega t \, dt. \qquad (2)$$

$$\text{Power Input} = \frac{E_0}{T} \int_0^T (i_A + i_B)\, dt. \qquad (3)$$

$$\text{Power Output } (P_0) = -\frac{E}{2T} \int_0^T (i_A - i_B) \sin \omega t \, dt. \qquad (4)$$

$$\text{Efficiency} = \frac{E}{2E_0} \; \frac{-\int_0^T (i_A - i_B) \sin \omega t \, dt}{\int_0^T (i_A + i_B)\, dt}. \qquad (5)$$

$$\text{Load Resistance} = \frac{E^2}{2P_0}. \qquad (6)$$

It is clear that curves *OPB* and *OC* of Figure 3 give all the information necessary to calculate the above quantities. If an amplitude E is assumed, the instantaneous values of $(i_A - i_B)$ and $(i_A + i_B)$ can be read from Figure 3 and then, by numerical integration, power input and power output can be evaluated from (3) and (4).

The conditions for maximum output and maximum efficiency can be determined by taking several values of amplitude. This analysis was carried out for the example of Figure 3; the results are shown in Figure 8. As could be expected, the peak output occurs at an amplitude nearly equal to *OP*, and the maximum efficiency occurs at somewhat lower amplitude.

In general, it is found that as the magnetic field is increased the crossing point *B*, of curve *OPB*, moves further out. The result is an increase in maximum output and efficiency.

In the above example, the maximum efficiency is about thirty-four per cent which by no means represents the best efficiency obtainable in a tube of this type. Unfortunately in the example given, the static curves could not be taken with higher magnetic fields because of

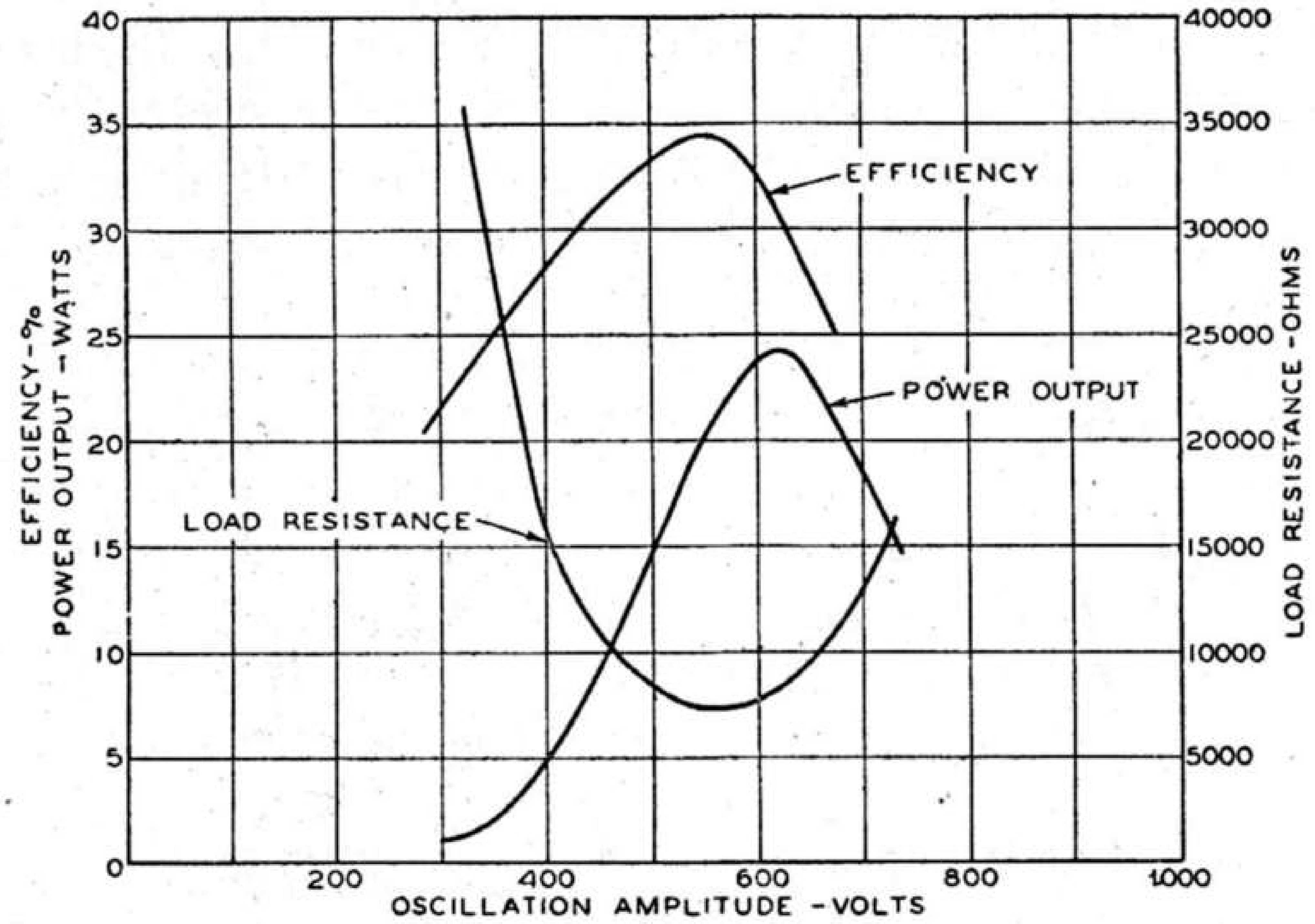

Fig. 8—Performance curves of a two-segment magnetron, calculated from the static characteristics.

problems of oscillation and electron bombardment of the leads. With higher magnetic fields, higher efficiencies may be expected. Megaw,[9] in a similar analysis, has calculated efficiencies as high as forty-five per cent for a tube operating under somewhat more favorable conditions than the above example.

IV. Limitations of Efficiency at Ultra-High Frequencies

Measured efficiencies of magnetrons at low and medium frequencies agree well with those predicted from the volt-ampere characteristics, but at very high frequencies it is found that the efficiency is considerably reduced. An experimental study of the efficiency of several magnetrons at very high frequencies was made to determine the main causes of decreased efficiency.

The problem of measuring efficiency at frequencies above 300 megacycles is very difficult because of the lack of a means of measuring power output, which is accurate and at the same time flexible enough to be used under a wide variety of conditions. The method finally adopted was that of absorbing power in a lamp previously calibrated photometrically on direct current. The obvious error in this method is the nonuniform heating of the lamp filament at high frequencies. However, it is estimated that, by the use of specially designed lamps, the error in the measurements was held to within plus or minus twenty per cent.

Figure 9 shows the measured efficiency as a function of frequency for plate diameters of 0.5 and 1.0 centimeter. When these curves were taken, the plate potential was held at 500 volts and the magnetic field

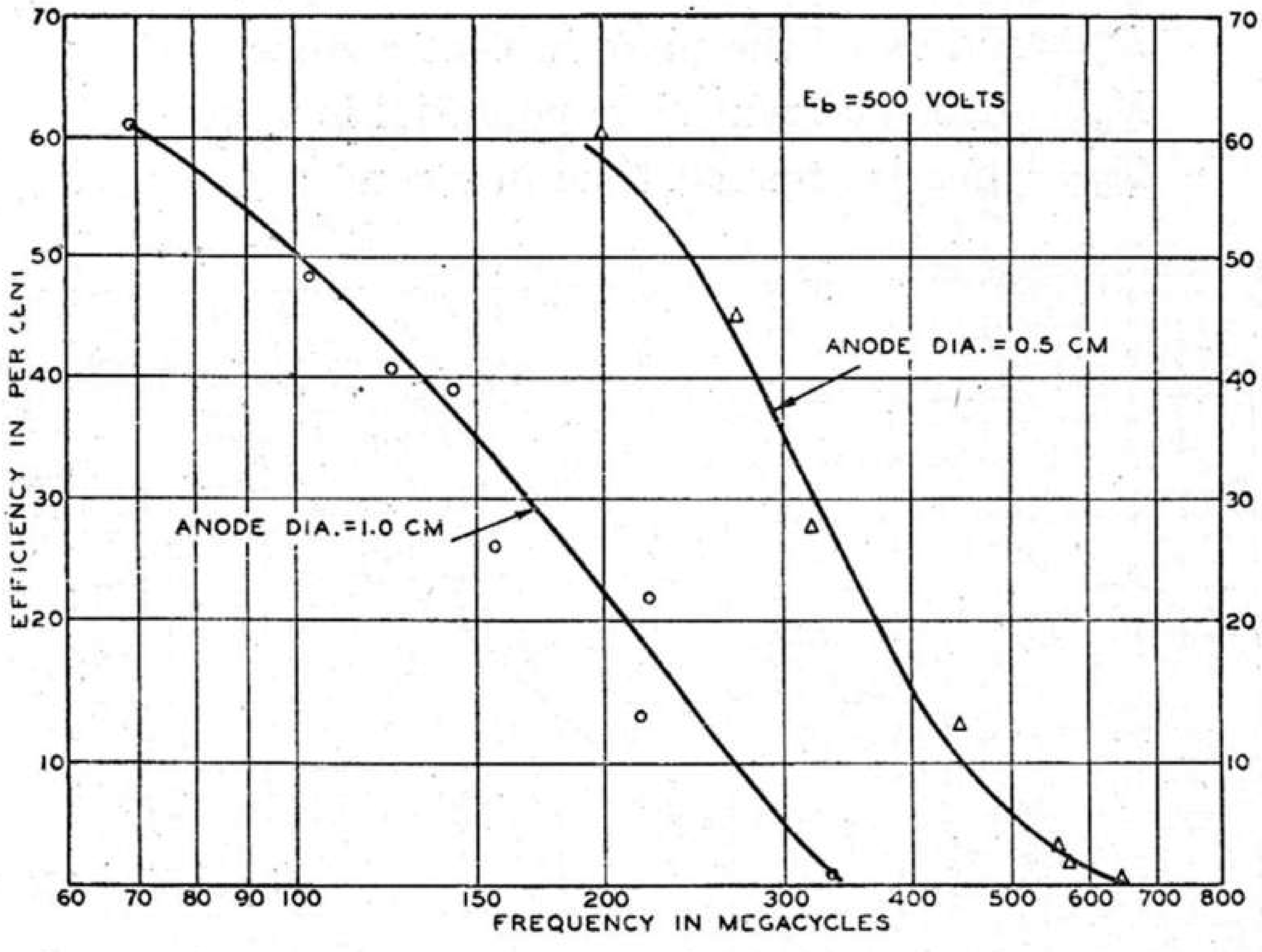

Fig. 9—Efficiency versus frequency for two sizes of magnetrons operating at the same plate potential.

was adjusted to give maximum efficiency at each point. The general shape of the curves for the two tubes is approximately the same; but, at a given efficiency, the frequency for the smaller plate diameter is roughly twice that for the larger. This seems to indicate that the higher efficiency for the smaller diameter tube is due to the shorter electron-transit time, and suggests that the decrease in efficiency at higher frequencies is because of the appreciable transit time.

If the efficiency is mainly a function of the ratio of transit time to period, then it might be expected that, at a given frequency, the efficiency will increase with plate voltage. This is borne out by the curve shown in Figure 10 where efficiency is plotted as a function of plate voltage for a tube operating at 440 megacycles. The tube used in this test had a plate diameter of 0.5 centimeter and was of the internal circuit construction described in Part V. The magnetic field for each reading was adjusted for the best efficiency.

To illustrate further the relation between efficiency and transit time, the efficiency data of Figures 9 and 10 with some additional data are plotted as a function of the ratio of transit time to period as shown in Figure 11. The value of transit time used is an effective direct-current transit time[19] given by the expression,

$$T_0 = 2.65 \times 10^{-8} \frac{R_a}{\sqrt{E_0}} \tag{7}$$

where,

R_a = radius of the plate in centimeters,
E_0 = direct-current plate potential in volts,
T_0 = effective transit time in seconds.

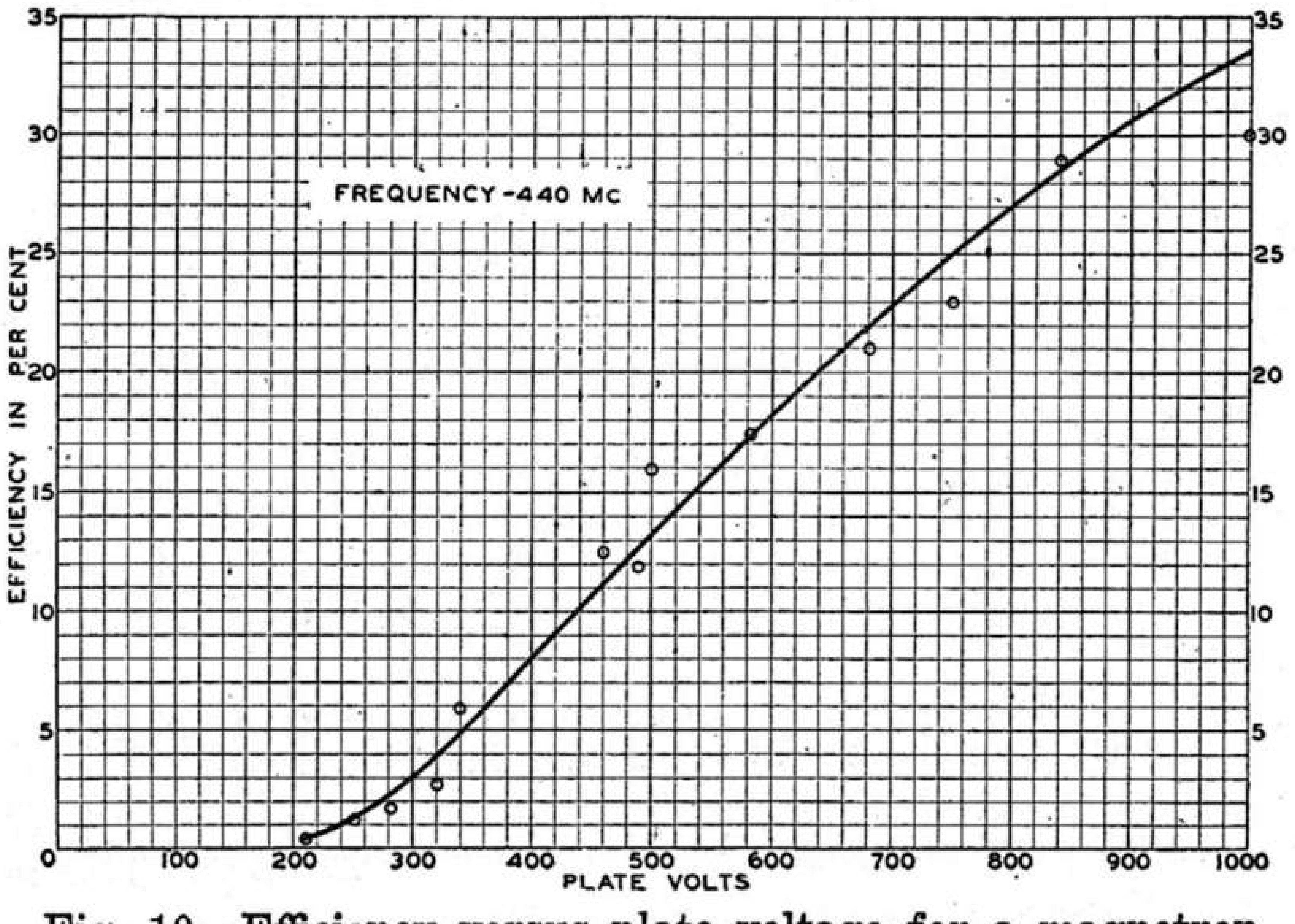

Fig. 10—Efficiency versus plate voltage for a magnetron operating at a frequency near the high-frequency limit.

The fact that all points from the several sources lie fairly close to a smooth curve is good evidence that the decrease in efficiency is, for the most part, due to transit-time effects. Examination of the curve shows that, if the transit-time ratio is below one-fifteenth of a period, efficiencies as high as fifty per cent can be expected, and that, even at

[19] The calculation of this transit time assumes a uniform velocity ($v_0 = 5.95 \times 10^7 \sqrt{E_0}$) and a semicircular path of a diameter equal to R_a. This transit time is equal to one half the orbital time of an electron traveling with a velocity v_0 in a magnetic field $H_c = 6.72/R_a \sqrt{E_0}$.

one-tenth of a period, thirty per cent efficiency is possible, but that, at one-fifth of a period, the tube will almost fail to oscillate.[20]

As a practical example, an efficiency of thirty per cent can be obtained at 600 megacycles with a tube having a plate diameter of 0.5 centimeter and a plate potential of 1500 volts.

Another factor to be considered in connection with attaining high efficiency at ultra-high frequencies is the value of magnetic field required. It is possible to demonstrate that, for a given efficiency and frequency, the value of the magnetic field is definitely determined,

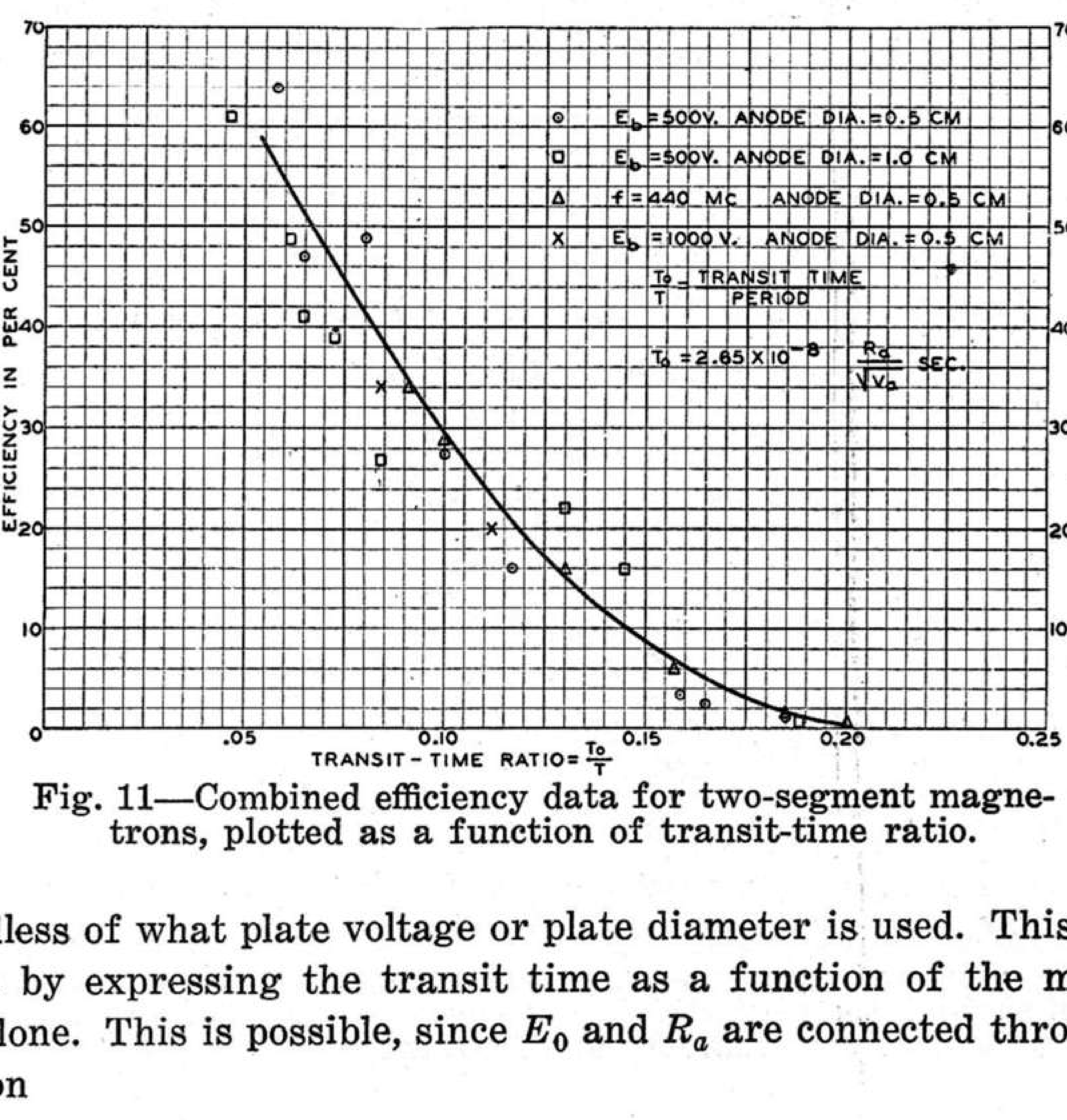

Fig. 11—Combined efficiency data for two-segment magnetrons, plotted as a function of transit-time ratio.

regardless of what plate voltage or plate diameter is used. This can be shown by expressing the transit time as a function of the magnetic field alone. This is possible, since E_0 and R_a are connected through the relation

$$H = k \frac{6.72}{R_a} \sqrt{E_0} \tag{8}$$

where k in practice lies between 1.5 and 2.0. Substituting (8) and (7) gives,

$$\frac{T_0}{T} = 1780 \frac{kf}{H} \times 10^{-10} \tag{9}$$

[20] When this general relation is compared with the data given by Megaw[9] a fairly good agreement is found. A similar comparison with the work of Slutzkin shows much poorer agreement, the efficiencies given by Slutzkin being generally higher.

where,

$$f = \text{frequency in cycles per second}$$
$$H = \text{magnetic field in gausses}$$
$$\frac{T_0}{T} = \text{ratio of transit time to period.}$$

This expression for transit-time ratio can now be combined with the efficiency curve of Figure 11 to give the magnetic field for any frequency and efficiency. This relation can best be illustrated by a chart of the type shown in Figure 12. The values of magnetic field obtained

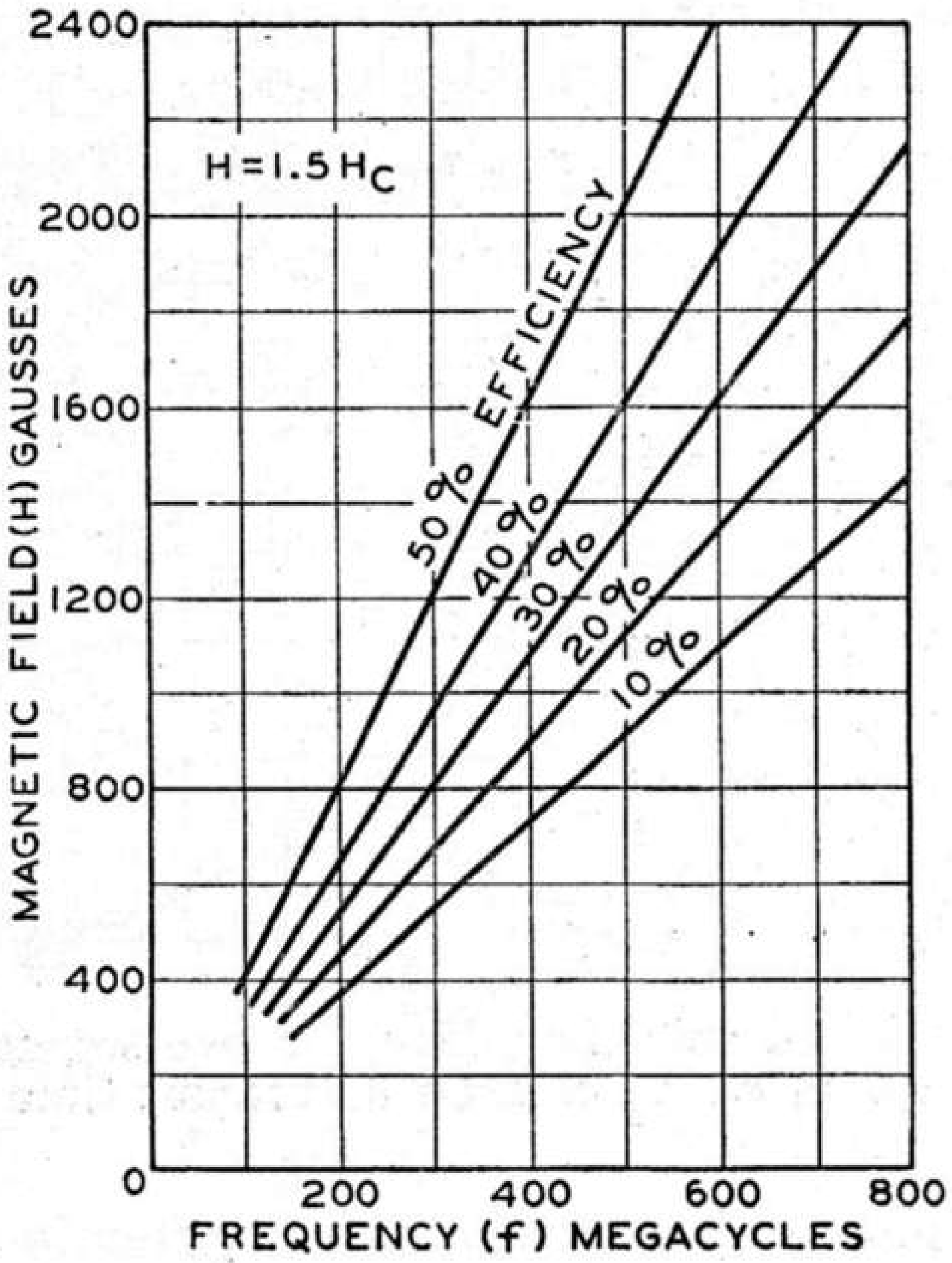

Fig. 12—Constant efficiency curves of a negative resistance magnetron showing the magnetic field strength required for any given efficiency and frequency.

from this diagram are only approximate because the value of k may vary considerably in practice and because the efficiency measurements are subject to a fairly large error.

It is interesting to compare the magnetic field required by a negative resistance oscillator to that required by an electronic oscillator operating at the same frequency. If the comparison is made on the basis of ten per cent efficiency (limit of electronic oscillator) it is found that the negative resistance magnetron requires approximately four times the field strength.[21]

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[21] This follows from the approximate relation for electronic oscillators that

$$H = 12{,}000/\lambda \text{ cm.}$$

In the discussion so far it has been assumed that circuit loss plays an unimportant role. This is contrary to the statement often made that circuit loss is the limiting factor in magnetron oscillators at ultra-high frequencies. However, it has been the experience of the author that, with proper care in design, circuits can be built which have negligible loss even at 600 megacycles. This is accomplished by using close-spaced leads to reduce radiation and by making the surface area of the leads sufficient to give small high-frequency resistance. A very low loss circuit has been obtained by the use of an internal copper circuit which will be described in Part V. The conclusion can be drawn that magnetron circuits can be designed so that the real limiting factor is the electron transit time.

V. Limitations in Plate Dissipation

The preceding analysis has shown that, for high efficiency in the 300- to 600-megacycle range, a small anode diameter is required (about

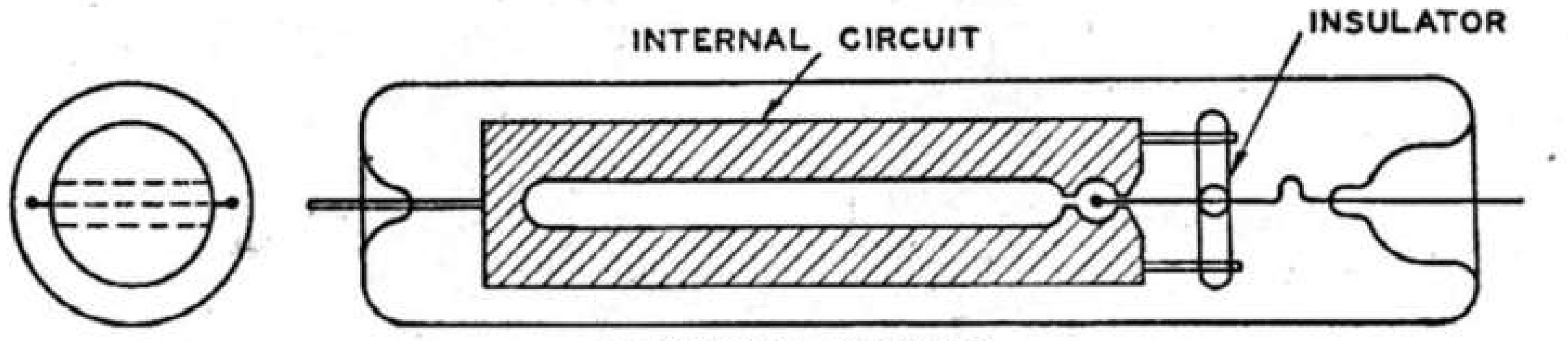

Fig. 13—Sectional view of an internal circuit radiation-cooled magnetron for obtaining high power at ultra-high frequencies.

0.5 centimeter for 1500 volts). It has also shown that a high magnetic field is required, a fact which limits the length of plate to a few centimeters for a magnet of reasonable dimensions. Both of these facts definitely limit the plate size and, consequently, impose a serious limitation on the possible plate dissipation. At first thought, it appears that the maximum dissipation of such a tube would be of the order of ten watts, but further study shows that this value can be increased by a large factor.

Although the dimensions of the plate cylinder are small, the radiating surface can be increased considerably by using a heavy walled plate to increase the outside area. The surface can be still further increased by placing the oscillating circuit within the bulb, as illustrated in Figure 13. When conductors of large cross section and good thermal conductivity are used the whole circuit is essentially at the same temperature, and its entire surface is effective in radiating heat. In this manner the radiating surface can be increased by a factor of the order of twenty to one.[22] Figure 14 illustrates a tube of this

[22] Shortly prior to the time at which the author constructed the first tube of this type, Mr. P. D. Zottu of this laboratory designed an internal circuit magnetron embodying the principal features described here.

construction which has a safe plate dissipation of 200 watts and will deliver an output of about fifty watts at a frequency of 550 megacycles with an efficiency of about thirty per cent. In this instance, the circuit was made of copper, which not only gives good thermal conductivity but also results in a very low loss circuit. To increase the emissivity the outer surface was carbonized. Incidentally, the carbonization may be expected to cause but little increase in the high-fre-

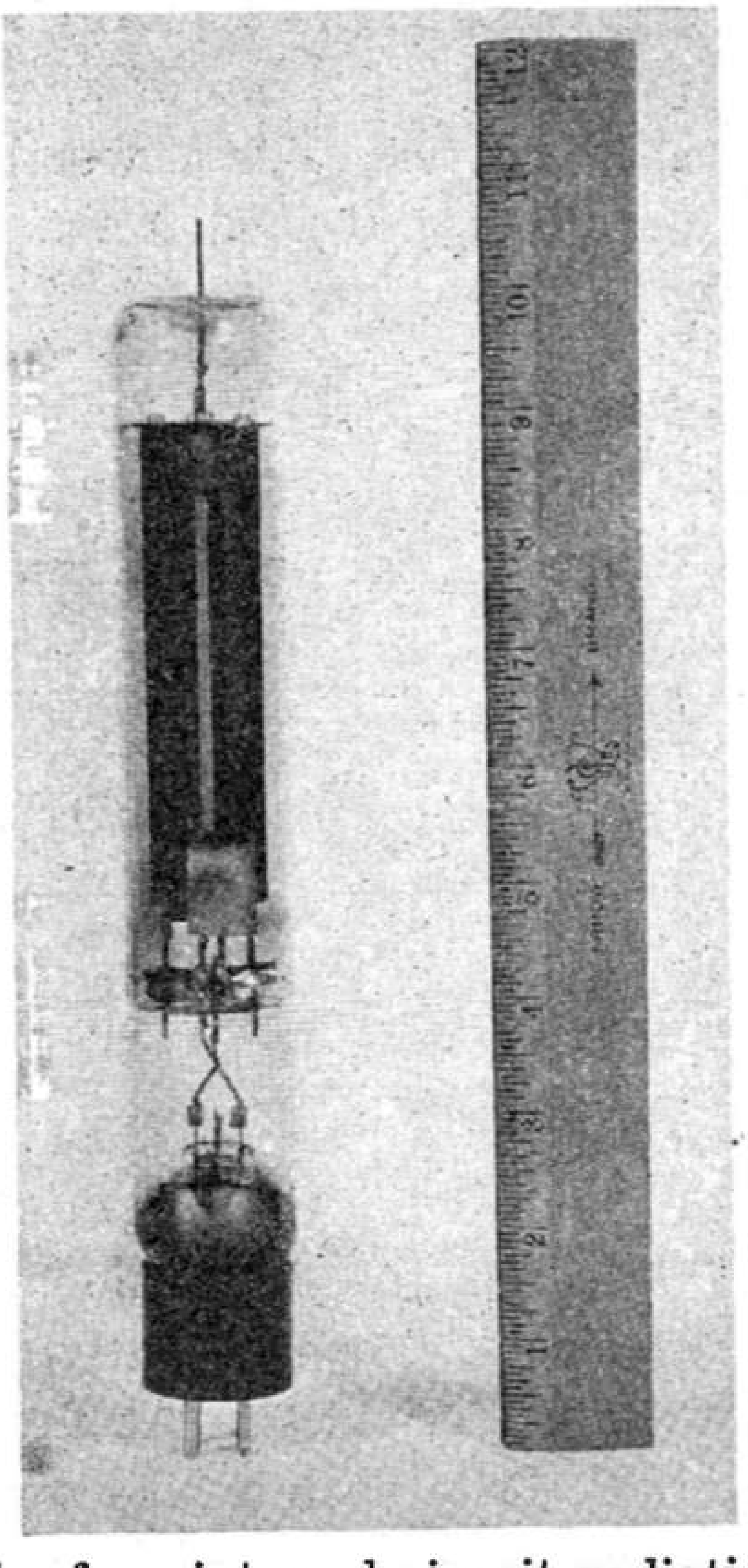

Fig. 14—Photograph of an internal circuit radiation-cooled magnetron oscillator for 550 megacycles.

quency resistance because most of the current in such a structure flows on the inner surface. The method of coupling this tube to the load was to use a parallel-wire transmission line, the closed end of which was inductively coupled to the internal circuit of the tube.

It is obvious that the internal circuit construction limits a given tube to operation over a relatively narrow frequency band. However, such a limitation may not be so serious in an ultra-high-frequency tube as it would be in a tube intended for lower frequency applications. Moreover, it may be pointed out that, aside from the advantage of high dissipation, the internal circuit construction becomes a necessity at frequencies around 400 megacycles, because of the impossibility of building external circuit tubes which will tune to such high frequencies.

To obtain still greater plate dissipation, it is necessary to resort to the use of some cooling liquid such as water. The problem of water-cooling in a split-anode magnetron for very high frequencies is not so simple as in the conventional three-electrode tube. In a magnetron, the power is dissipated over a comparatively small area. This makes it necessary to conduct the heat away to a larger surface which can be effectively water-cooled. There are a number of ways in which this can be accomplished; one example is illustrated by Figure 15. Here, also, an internal circuit of heavy copper conductors is used, but in this case the circuit is conductively coupled to the load by two leads brought out in a plane at right angles to the plane of the filament leads. Figure 16 shows a photograph of a laboratory tube of this construction with an internal circuit and plate of approximately the same

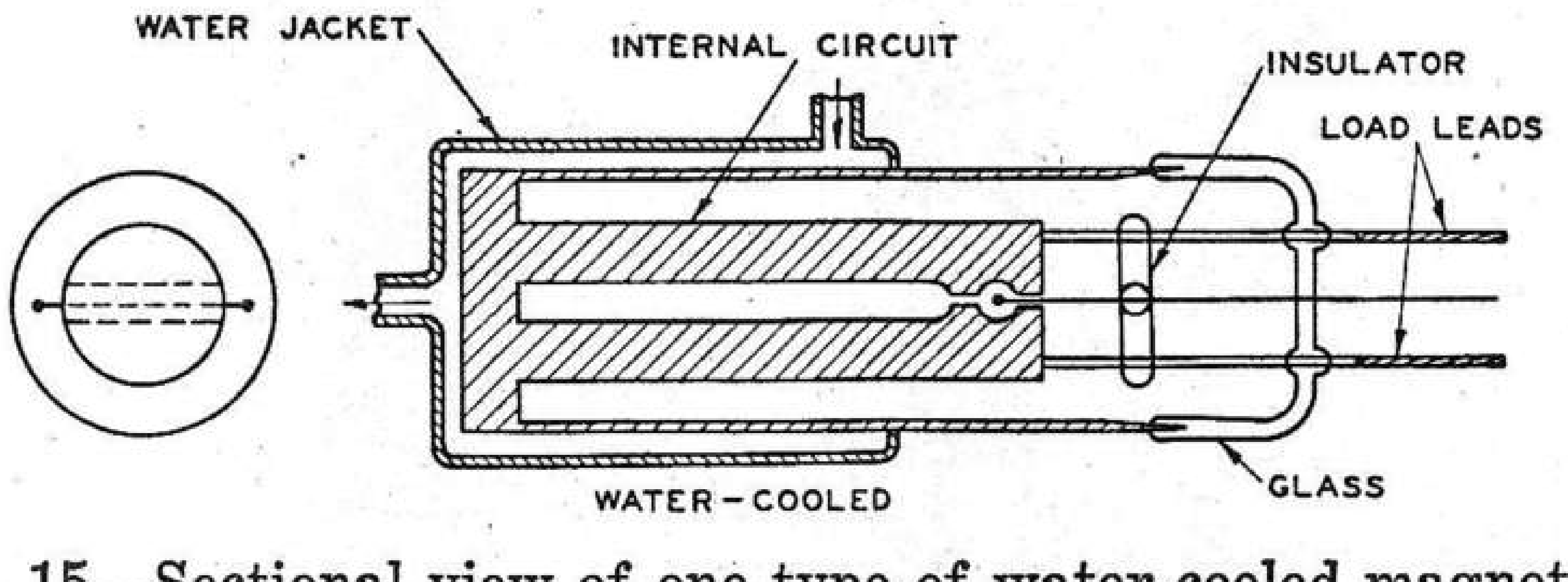

Fig. 15—Sectional view of one type of water-cooled magnetron for high power at ultra-high frequencies.

dimensions as the radiation-cooled tube of Figure 14. This particular tube will dissipate more than 500 watts and will deliver an output of approximately 100 watts at a frequency of 600 megacycles with an efficiency of about twenty-five per cent.

VI. Miscellaneous Limitations

Besides the factors discussed in the previous sections, there are two other factors that limit to some degree the output obtainable from a magnetron oscillator. One of these, existing in radiation-cooled tubes, is the electron bombardment of the glass walls opposite the ends of the plate due to the focusing effect of the magnetic field. A solution to this problem has been found by adding shielding electrodes at the plate ends. Shielding electrodes of this type can be seen in the illustration of Figure 14.

The other factor which is somewhat more serious is a phenomenon termed "filament-bombardment effect." This effect, observed by the author several years ago, has been mentioned by a number of writers on magnetrons.[23] The effect manifests itself as an increase of filament temperature under certain conditions of high magnetic field and high plate voltage, and sometimes results in unstable operation of the tube.

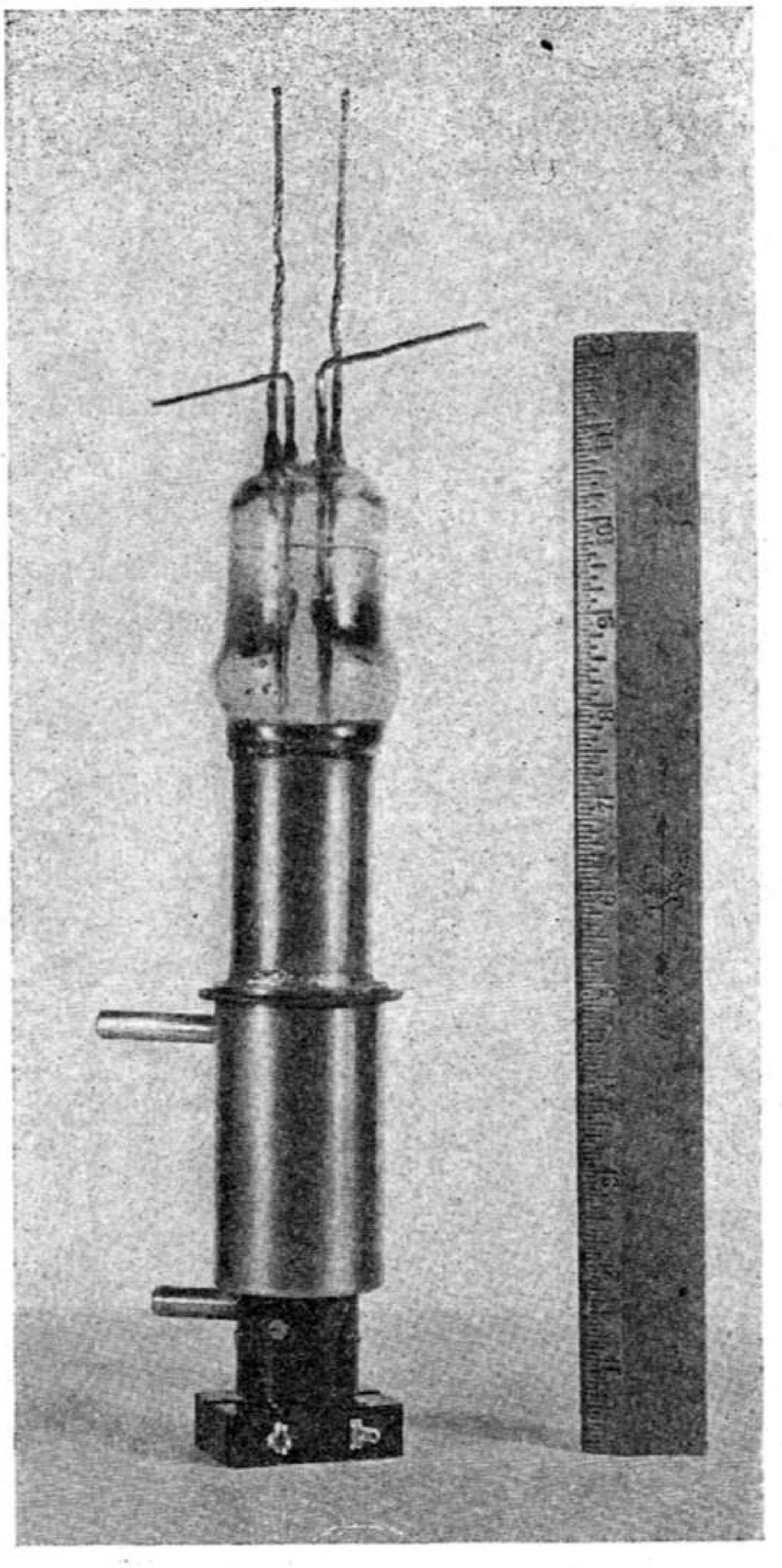

Fig. 16—Photograph of a water-cooled magnetron oscillator for 600 megacycles.

[23] Megaw,[24] Slutzkin[25, 26] and others have described this effect and Langmuir and Found[27] have observed a related phenomenon in connection with electron scattering.

[24] E. C. S. Megaw, "A New Effect in Thermionic Valves at Very Short Wave Lengths," *Nature*, Vol. 132, p. 854; December 2 (1933).

[25] A. A. Slutzkin, S. J. Brande, and I. M. Wigdortschik, "Generation of ion currents in high vacuum by the help of magnetic fields," *Phys. Zeit. der Sowietunion*, Vol. 6, pp. 268-279 (1934).

[26] A. A. Slutzkin, et al., "Production of Electromagnetic Waves Below Fifty Centimeters," *Phys. Zeit. der Sowietunion*, Vol. 6, pp. 150-158 (1934).

[27] I. Langmuir, "Scattering of Electrons in Ionized Gases," *Phys. Rev.*, Vol. 26, pp. 585-613 (1925).

In extreme cases, the filament can receive sufficient energy from the plate circuit to permit operation of the tube with the usual filament supply disconnected. The cause of this phenomenon has not been fully explained, but it appears to be due to a bombardment of the filament by electrons.

Although the filament-bombardment effect is sometimes troublesome, it can generally be avoided by using heavy filaments and by operating the tube at somewhat reduced plate voltage and magnetic field strength.

VII. Conclusion

It has been demonstrated by theory and experiment that the negative resistance magnetron is essentially a high efficiency device at low frequencies, and that the decrease of efficiency at high frequencies is mainly due to transit-time effects. As applied to frequencies between 300 and 600 megacycles, it is shown that this type of oscillator can be expected to give efficiencies of the order of fifty to thirty per cent.

Methods are described by which the inherently small plate-dissipation limit can be extended by twenty to fifty times, and by which it is possible to realize power outputs of the order of fifty to 100 watts in the 300- to 600-megacycle range. The output and efficiencies obtained compare favorably with those of conventional tubes at much lower frequencies, but it is not to be inferred that magnetrons will necessarily supplant other types of generators. Problems of modulation and frequency stability are still to be met and in some applications the supplying of a high magnetic field may be inconvenient.

In conclusion, the author wishes to point out that the specific tubes described are not to be regarded as commercial designs. They are, rather, laboratory tubes built to demonstrate certain principles which, it is hoped, will prove useful in future designs of ultra-high-frequency generators.

Acknowledgment

The writer desires to express his indebtedness to Mr. B. J. Thompson and Mr. H. C. Thompson for many helpful suggestions, and to Mr. T. H. Clark for his assistance in the experimental work.