The Magnetron as a High Frequency Generator*

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I. Introduction

THE search for methods of generating ultra-high frequencies has followed two main paths. One has been the improvement of the negative grid tube as an oscillator and amplifier so as to extend its upper frequency limit. The other has been the investigation of less conventional vacuum tubes that appear to be applicable at high frequencies. Of the latter group the magnetron now stands out as one of the most promising tubes.

The device first called a "magnetron" by Hull[2] in 1921 is well known as a vacuum tube having a cylindrical plate structure and coaxial filament, with a uniform magnetic field directed along the electrode axis. Its use as a generator of high frequency currents has developed mainly in the past decade and its investigation has claimed the attention of a large number of research workers in many countries.

Magnetrons in a variety of structural forms and in a number of operating modes have been used for oscillation generation. Broadly speaking, magnetron oscillators can be divided into two classes; one using an alternating magnetic field, and the other using a constant magnetic field. The alternating-field type described by Elder,[3] in which the field coil is part of the oscillating circuit, is obviously limited to low frequencies and need not be considered in the present discussion. The constant field types which are useful in generating ultra-high frequencies can be subdivided as negative resistance oscillators and transit time oscillators.

The negative resistance magnetron oscillator may be 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 period of the circuit. In Europe this type is sometimes called "dynatron magnetron" or Habann oscillator.

The transit time magnetron oscillator may be defined as one which operates by reason of electron transit time phenomena and in which the frequency is determined by the electron transit time. This type is often referred to as an "electronic oscillator" and sometimes as a "magnetostatic oscillator."

It is the purpose of the present paper to survey the various types of magnetron generators with particular reference to their performance and limitations at ultra-high frequencies.

II. Negative Resistance Magnetrons

In reviewing magnetron oscillators, it is well to begin with the negative resistance magnetron since its operation is more nearly like that of conventional tubes. Historically, the basic idea of the negative resistance magnetron was disclosed by Habann[4] in 1924, and the common push-pull arrangement of the split-plate magnetron was introduced by Manns[6] in 1927. Since that time a number of papers on the application of this device to the generation of ultra-high frequencies have appeared.[11, 13, 18, 30]

The tube in its usual form consists of two semicylindrical plates with a co-axial filament and is operated in a circuit as shown in Fig. 1. In order to start oscillations the magnetic field directed

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along the axis of the tube must be increased to a value slightly above the critical value[1]

$$H_{cr}=6.72E_p^{\frac{1}{2}}/r_p \text{ gauss},$$

where E_p = plate potential in volts,
r_p = plate radius in centimeters,

under which condition the electrons miss the plate on their first passage. After oscillations are started, the magnetic field can be increased to a much higher value and its adjustment is not particularly critical.

The reason for oscillation can be explained on the basis of a static negative resistance characteristic of the type shown in Fig. 2. This characteristic is obtained by measuring the current to the plate halves as the potential on one is increased by increments and the potential on the other is decreased by the same increments, so as to simulate conditions during oscillation. It can be seen from this curve that at first more current flows to the plate at lower potential and that, as the difference of potential (E_A-E_B) is increased, the excess of current to plate B increases, resulting in the negative resistance curve OP. If this negative resistance is low enough, self-sustained oscillations can be produced in a tank circuit connected across the two plates.

A good physical picture as to the reason for the negative resistance characteristic can be found by turning briefly to a study of electron paths. Figs. *3a*, *3b*, *3c* illustrate typical electron paths which were estimated from the electrostatic and magnetic fields. Fig. *3a* shows the case of equal potentials on the plate halves under which condition the electrons travel in symmetrical paths, very few reaching either plate. When the plate halves are at different potentials, the electrons describe more complicated paths, usually landing on the plate at lower potential, either as shown in Fig. *3b* or Fig. *3c*. In these examples the magnetic field is approximately 1.5 times the critical value. Electron paths of this type have been clearly demonstrated in a special gas-filled beam magnetron which makes the beam trace visible by ionization.[30] A photograph of a beam trace of this type is shown in Fig. *3d*.

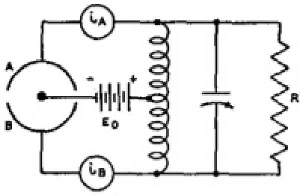


FIG. 1. Two-segment magnetron oscillator circuit.

The static curves shown in Fig. 2 can be used to calculate power output, efficiency and load resistance. From computations of this sort which have been made by several investigators,[13, 30] it can be concluded that at low frequencies an efficiency comparable to that of the feed-back oscillator is to be expected, and that the load impedance required for optimum output is somewhat higher.

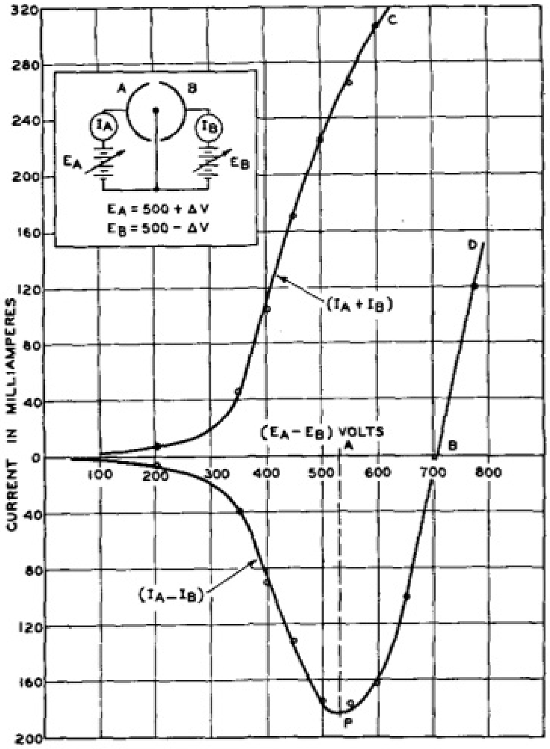
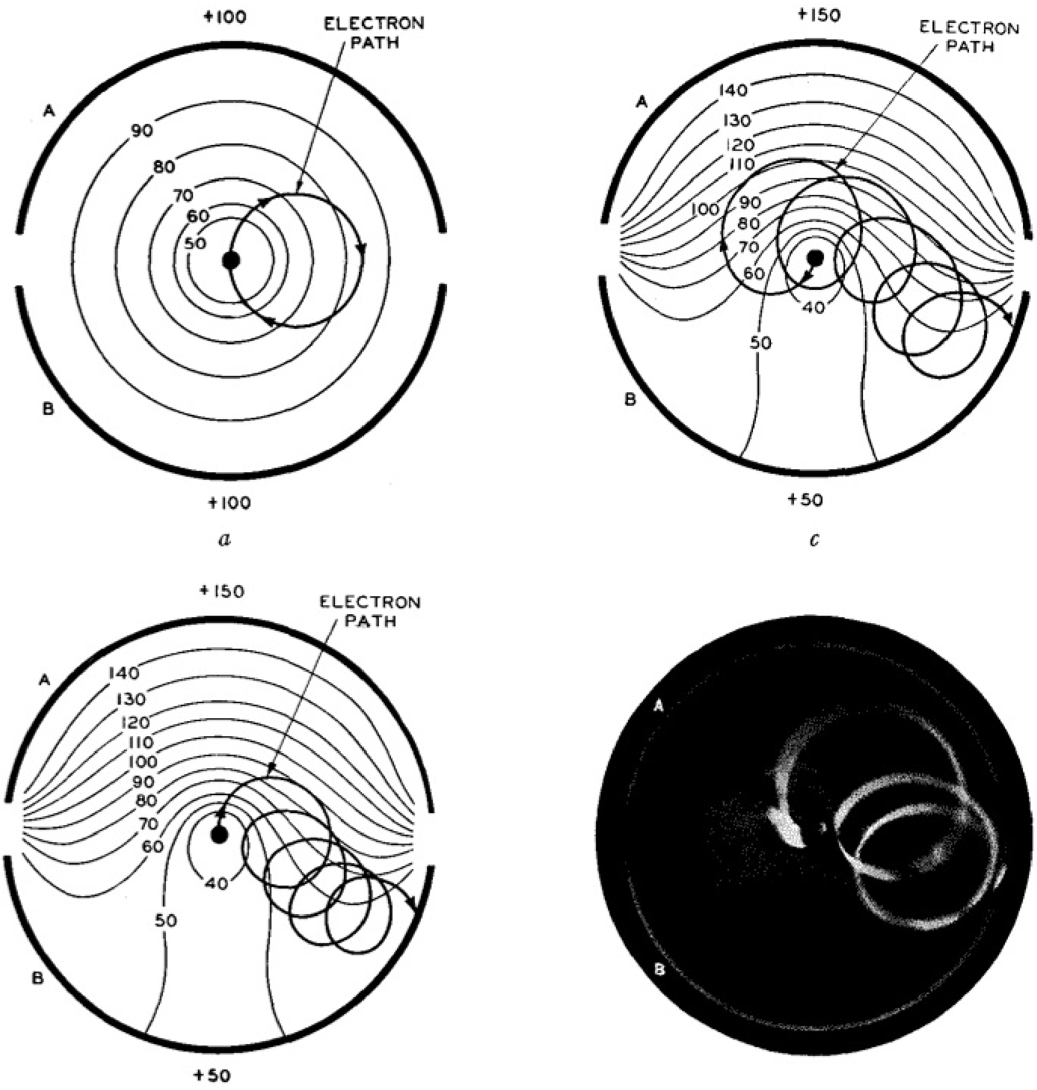


FIG. 2. Static characteristics of a two-segment magnetron showing negative resistance.

Performance at High Frequencies

Although the high efficiency predicted from the static characteristics can be demonstrated at low and medium frequencies, it is found on going to very high frequencies that the efficiency decreases much in the same manner as for the negative grid oscillator. Typical curves of efficiency *versus* frequency are shown in Fig. 4. This decrease in efficiency was first ascribed mainly to circuit losses, but later it was demonstrated that even with circuits of negligible loss the efficiency still decreased at extreme frequencies, and in a manner to suggest electron transit time effects.



a *c*

b *d*

FIG. 3. Typical electron paths in a two-segment magnetron, showing how electrons arrive at the plate-half of lower potential.

This point is made clear by Fig. 5 where efficiency data are plotted against the ratio of electron transit time to period, for several tubes of various plate diameters and plate voltages. The transit time figure used is somewhat arbitrary, being approximately one-half the time required for an electron to describe a complete orbit. It is numerically equal to $2.65\times10^{-8}\,r_p/(E_0)^{\frac{1}{2}}$ seconds. The fact that all these data fall quite close to a smooth curve is evidence that the decrease in efficiency is due to transit time effects.

These data from the author's paper[30] show the same general trend of efficiency, as found by most of the other workers in the field. For example, Fig. 6 shows a curve taken from a paper by Herriger and Hulster.[27] Here efficiency is plotted against a factor which the Germans term the "order" of oscillation. This is the number of electron orbits described per period, or one-half the reciprocal of the abscissa of the previous curve. These data, when compared on the same basis, agree fairly well with that of the author. Megaw,[29] however, in a recent paper states that the efficiency increases in the intermediate region just before the limiting frequency is reached. He accounts for this by transit time effects but does not show any experimental data to substantiate his statements.

The general efficiency curve of the type shown in Fig. 5 is very useful in predicting performance. It shows that for reasonably high efficiency, the transit time must be one-tenth period or less. This means that for high efficiency at high frequencies either high plate voltage or small plate diameter must be used. For example, to obtain 40 percent efficiency at 50 cm wave-length with a plate diameter of 0.5 cm, a plate potential of 1600 volts is required.

In addition to these requirements, it can be shown that a high magnetic field is required, since the magnetic field strength is connected with transit time in a more fundamental way than either plate voltage or plate diameter. This follows directly from the fact that the orbital time of an electron is nearly inversely proportional to the magnetic field strength. This reveals the important fact that for a given frequency and efficiency the value of magnetic field required is determined regardless of what plate voltage or plate diameter is used. As an example, for 30 percent efficiency at 50 cm wave-length, a field strength of approximately 1600 gauss is required, while for the same efficiency at 5 cm wave-length, 16,000 gauss would be required. The field strength required is clearly a serious factor in applying the negative resistance magnetron to extreme frequencies.

Circuit Limitations

In the foregoing work the circuit limitations were for the time neglected. However, the circuit problem is important in the negative resistance magnetron as well as in the negative grid oscillator, particularly when an attempt is made to obtain very short wave-lengths. The circuit appears as a limitation in two ways; first, the size of circuit becomes so small as to allow little or no circuit external to the tube; and second, the circuit losses increase with frequency and thus decrease overall efficiency.

At wave-lengths around 50 cm, it becomes necessary to mount the whole oscillating circuit within the tube envelope. An illustration of this is shown in Figs. 7 and 8. The internal circuit is inductively coupled to the load through a loop not shown.

The importance of low loss, high impedance circuits is seen when it is considered that for the usual negative resistance magnetron the optimum load impedance calculated from static curves is from 5000 to 10,000 ohms. This means that in order to keep the circuit loss down to a reasonable value, circuit impedances of 25,000 to 50,000 ohms must be used.

The circuit losses are largely due to skin effect and radiation. The first can be minimized by using conductors of low resistivity material having fairly large surfaces. The second can be

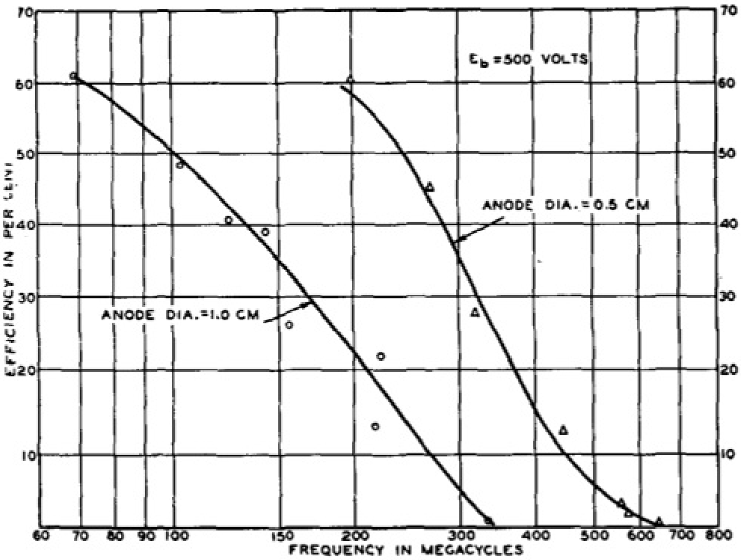


FIG. 4. Efficiency of a two-segment magnetron as a function of frequency.

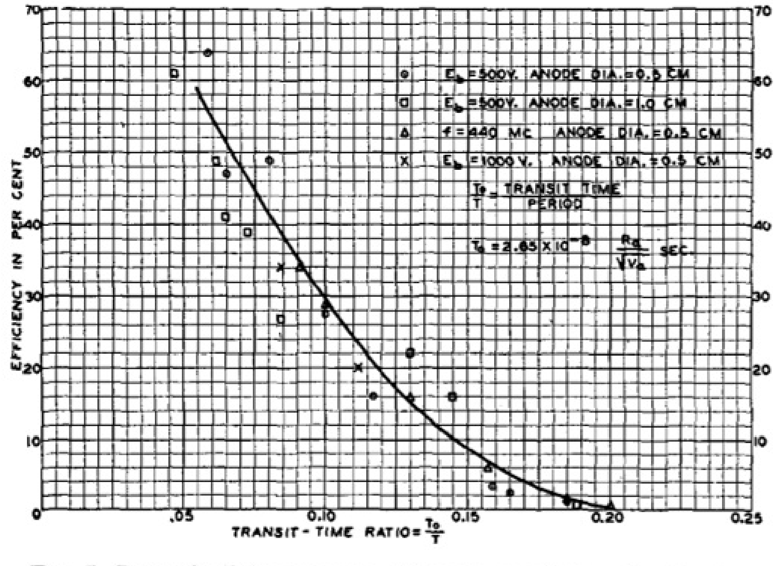


FIG. 5. General efficiency curve of two-segment magnetrons as a function of the ratio of electron transit time to period.

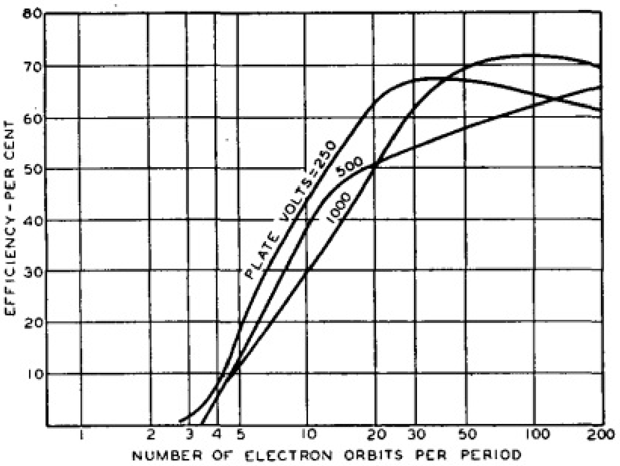


FIG. 6. Efficiency curves of a two-segment magnetron as a function of the number of electron orbits per period. From the paper by Herriger and Hulster.

minimized by using close spacing of the leads (of the order of 1/100 wave-length). However, to secure optimum design of circuit for a given tube capacity, there must be a compromise between the two losses since decreasing the conductor spacing beyond a certain point increases the conductor loss.

As to practical cases, little data are yet available, but it is safe to say that circuit impedances as high as 25,000 ohms can be obtained at wave-lengths as short as 50 cm. But, as the frequency is increased, the problem becomes more serious due to the fact that if circuit dimensions are decreased in proportion to wave-length the impedance decreases as the square root of the wave-length.

There is one compensating factor, however, in that there is apparently some decrease in dynamic impedance of the tube at the higher frequencies where transit time effects come into play.[29]

Output Limitations

The requirements of high plate voltage and small anode size for high efficiency both make for high plate dissipation per unit area. Plate dissipation therefore becomes one of the most serious factors in limiting output of the negative resistance magnetron at high frequencies.

Some progress has been made in the way of increasing dissipation limit and output by using a heavy walled plate structure to increase the radiation surface. Still further increase in dissipation has been obtained by placing the oscillating circuit within the tube envelope as shown in Fig. 7. The conductors being of large cross section and of good thermal conductivity, the whole circuit serves to dissipate heat. By this means the effective radiation surface can be increased by a factor of about 20 to 1. A tube of this type built in the RCA Radiotron Laboratory is shown in Fig. 8 which will deliver approximately 50 watts output at a wave-length of 55 cm.[30]

Still larger increase in output has been obtained by water cooling the plate surface. One type of water cooled tube is shown in Fig. 9. A tube of this construction gave a useful output of approximately 100 watts at a wave-length of 50 cm.[30]

Another effective means of water cooling described by Pfetscher and Puhlmann[28] of the University of Jena is shown in Fig. 10. The water cooling combined with continuous exhaust allowed these tubes to be operated at voltages several times higher than normally used, with a consequent increase in output. One tube of the type shown in Fig. 10b gave an output of 450 watts at a wave-length of 46 cm, and a smaller tube gave 80 watts output at 19 cm. This represents the best performance reported so far for negative resistance magnetrons and is far above the outputs obtainable at these wave-lengths by any other means.

III. **Transit Time Magnetrons**

The second class of magnetrons for generating ultra-high frequencies as defined above is characterized by the fact that the frequency is determined by the electron transit time. Oscillators of this type are of importance because they are capable of generating currents at extremely short waves.

The first record in the literature of transit time magnetrons is that of Zacek[5] who in 1924 dis-

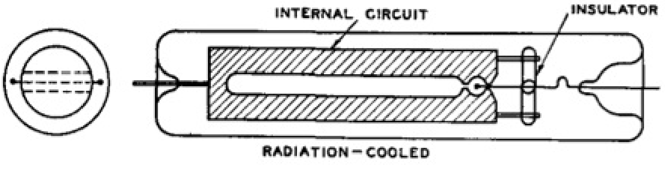


Fig. 7. Sectional view of an internal circuit radiation cooled magnetron for obtaining high power at ultra-short waves.

covered oscillations in a cylindrical diode. Not much importance was attached to this kind of generator until Okabe[7] in 1928 showed that a much larger output could be obtained by a split-plate construction such as had already been used by Habann and Manns for negative resistance oscillators. Okabe expressed the empirical relation that the wave-length

$$\lambda = 12{,}000/H_{\text{gauss}} \text{ centimeters,}$$

which corresponds to the condition that the period of oscillation is approximately equal to the orbital time of the electron.

The plate construction and circuit arrangement are usually the same as for the negative resistance magnetron. The operating conditions, however, are somewhat different. The magnetic field must not only be adjusted near critical but must also be at a particular value for a given wave-length. This means that plate voltage and field strength are both critical in adjustment. In addition, it has been found that the magnetic field must be inclined at an angle of a few degrees to the tube axis.[9, 10, 12]

The basic mechanism of this type of oscillator is best explained by considering two groups of electrons; one which absorbs energy from the circuit, and the other which delivers energy to the circuit. The loss electrons are those reaching the slot field just in time to be given an accelerating impulse which will in general cause them to be absorbed by the plate with a resulting energy loss.

The useful electrons are those reaching the slot field in the proper time to be decelerated. These electrons give up an increment of energy and thereby miss the plate, describing several orbits, each time reaching the slot region in proper phase to give up energy, the orbital time being equal to one period. Under proper conditions the net effect is that more energy is given up to the circuit by the useful group than is absorbed by the loss group, and thus self-sustained oscillations can exist.

The tilting of the field is apparently necessary in order to draw the electrons out of the electrode space before they make too many trips, which would result in an excess space charge, and in turn would effect the orbital time, causing the electrons to get out of phase. It is also probable that the orbital time of an electron differs slightly on successive orbits so that in general an electron cannot make very many orbits before getting out of phase. It is therefore desirable to withdraw an electron before it gets out of phase and results in energy absorption.

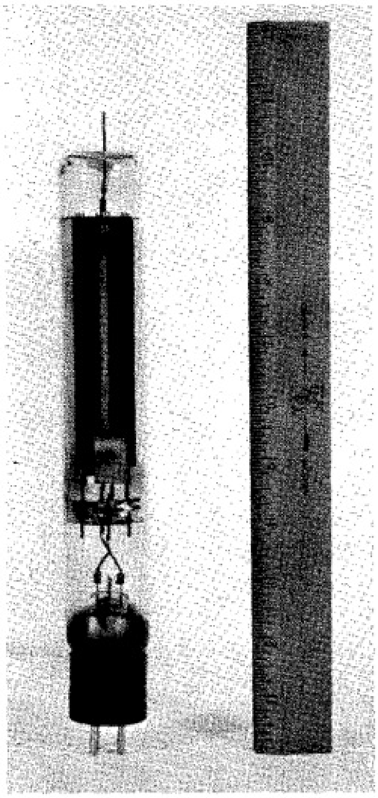


FIG. 8. Photograph of an internal circuit radiation cooled magnetron for a wave-length of 55 cm.

Unlike the negative resistance magnetron, the transit time tube is very critical to filament emission and requires a much smaller emission for optimum output. Usually, the optimum plate

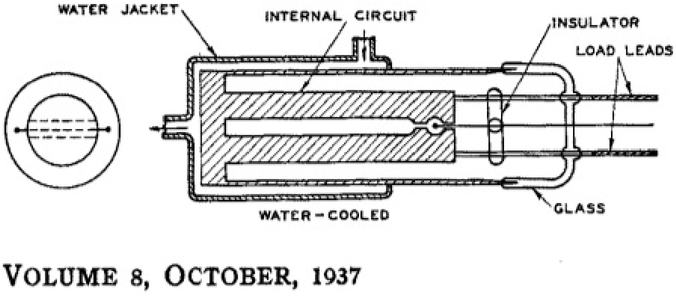


FIG. 9. Sectional view of one type of water cooled magnetron for ultra-short waves.

current is reached before the plate dissipation limit occurs.

It has been found experimentally that a given tube can deliver appreciable output only over a limited range of frequency. The output drops at the lower frequencies because of reduced voltage required and is limited at the high frequency end due to a type of instability called "filament bombardment" which will be discussed later. Empirical relations useful in design of these tubes are that the optimum anode diameter is about 1/20 of the wave-length, and the useful frequency range is approximately 2 to 1. To cover a wide range of frequencies with the transit time magnetron, a large number of tubes of different sizes must be used.

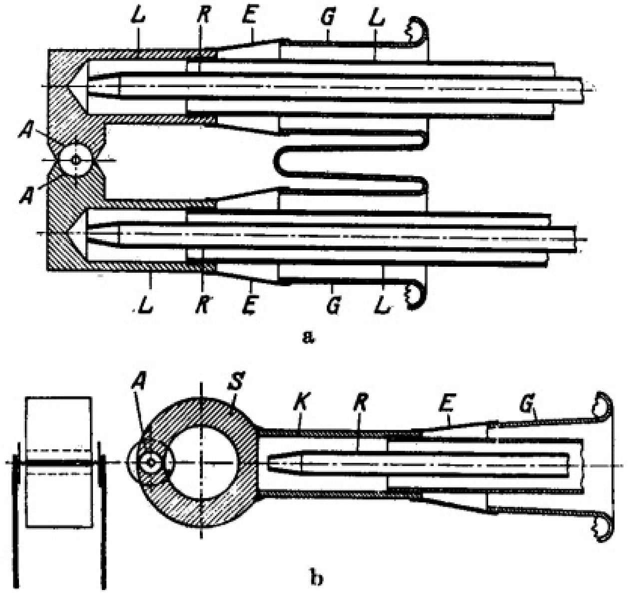


FIG. 10. Sectional view of two types of water cooled magnetrons described by Pfetscher and Puhlmann.

The usual efficiency obtained with the 2-plate transit time magnetron is around 10 percent, while for the diode type it is about 1 percent.[12] The output obtainable is a function of the wave-length, varying from about 10 watts at 50 cm, to 1 or 2 watts at 10 cm.

The diode magnetron has not been commonly used because of its extremely low efficiency. However, C. W. Rice[33] of the General Electric Laboratories has recently described a diode magnetron giving several watts output at 5 cm wave-length. The comparatively large output is obtained by using a water cooled tube with several hundred watts input.

An interesting feature of the transit time magnetron is that due to its basic mechanism it can be operated into a much lower impedance load than the negative resistance magnetron, and so does not require a circuit of such high impedance. This comes about from the fact that a small amplitude of potential on the plate halves can give rise to a large circulating electron current which in an ordinary tube would require much higher voltage amplitude. Experimentally, it has been found that transit time magnetrons will work into a load resistance of the order of one-tenth that of the negative resistance magnetron and that oscillations can be sustained in circuits with an impedance of the order of 100 ohms. This is one reason why it has been possible to operate these tubes at such extreme frequencies where the circuits are unquestionably very poor.

Another factor in favor of the transit time generator is that it requires a much smaller magnetic field for a given frequency. This follows directly from the fact that in negative resistance oscillators the electron transit time must be a much smaller fraction of the period than in the transit time type. The transit time for the latter type is of course one-half period while for the negative resistance type operating at the same efficiency it must be less than one-eighth period (see Fig. 5). The negative resistance magnetron, therefore, requires approximately four times the field strength for a given frequency.

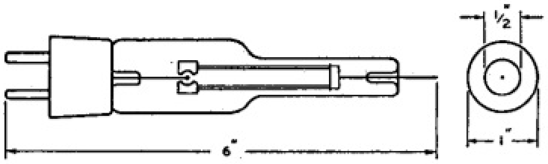


FIG. 11. Early type of internal circuit transit time magnetron for generating 9 cm waves (Westinghouse Electric and Manufacturing Co.).

Improved Types

Since the advent of the split-plate construction, two major improvements in transit time magnetrons have been made; namely, the use of an internal circuit construction for obtaining extremely high frequencies, and the use of the end-plate construction.

In 1932, transit time magnetrons of the internal circuit type were built in the Westinghouse Laboratories[15] for the generation of 9 cm waves.

An early tube of this type is shown in Fig. 11. In this tube the circuit is slightly more than one-half wave-length long. The shorting bridge is at the second voltage node, the first node occurring less than a millimeter from the plate. The circuit is coupled inductively to the load. Still smaller tubes with internal-circuit constructions have been described by Williams and Cleeton.[17, 22, 34] These tubes were used to generate high frequency currents at wave-lengths as short as 6 millimeters.

The second improvement came with the end-plate magnetron disclosed by Linder[20] of the RCA Victor Laboratories. This tube is similar to the split-plate magnetron except that two electrodes are added at the end of the plate cylinder. These end plates are maintained at a positive potential slightly lower than that of the split plates. The construction of the end-plate magnetron is clearly shown in Fig. 12. In this tube an internal circuit is used with a shorting bridge placed at the first voltage node, with a transmission line brought out to the load.

Linder[25] has shown that end plates serve the same purpose as tilting the magnetic field, in removing electrons from the interelectrode space after they have made several orbits. He has found that the end-plate tube gives somewhat higher output and efficiency than the simple split-plate tube and that it is easier to stabilize. He has reported an output of 2.5 watts and 12 percent efficiency at a wave-length of 9 cm, as compared to about 1 watt and 8 percent efficiency obtained from tubes without end plates.

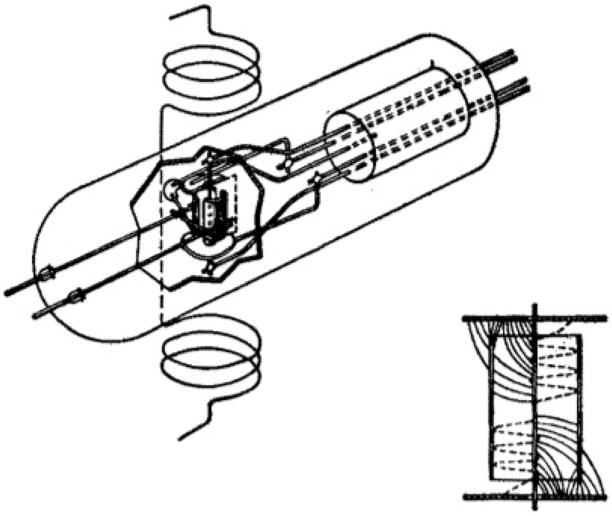


FIG. 12. End-plate magnetron showing internal circuit and transmission line.

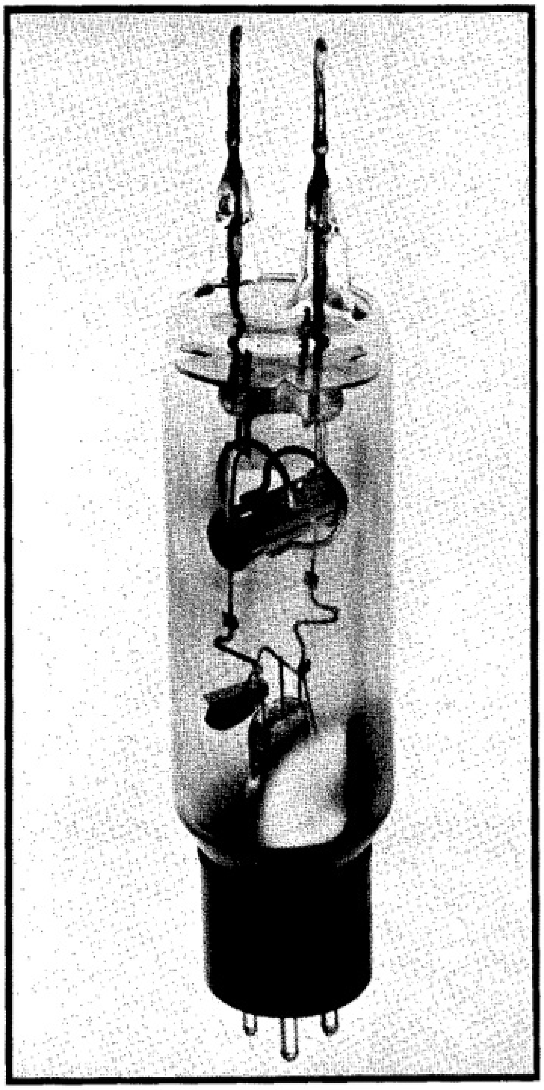


FIG. 13. Four-segment magnetron with internally connected segments.

Multi-Segment Tubes

A survey of magnetrons would not be complete without some mention of tubes having more than two segments, particularly the four-segment construction. A four-segment tube was described in the literature as early as 1928 by Yagi.[8] In the past few years considerable attention has been given to this tube, particularly in Europe.[21, 27] In the common construction of these tubes, opposite pairs of plates are connected together and only a single pair of leads is brought out as shown in Fig. 13. There appears to be considerable controversy both as to the theory of operation and to the actual performance of these tubes.

The four-segment tube, like the two-plate tube, has static negative resistance, but as it is norm-

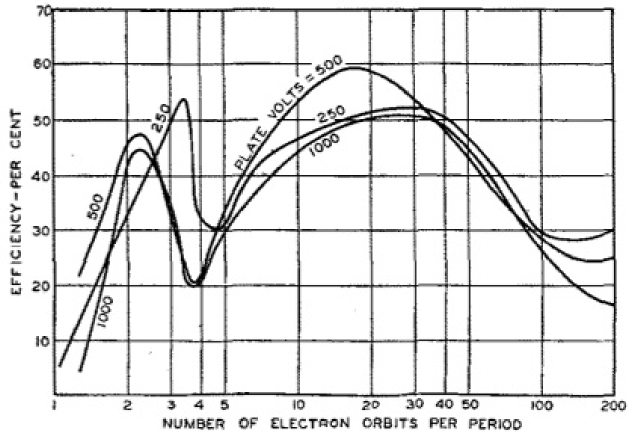


FIG. 14. Efficiency curves of a four-segment magnetron as a function of the number of electron orbits per period. From the paper by Herriger and Hulster.

ally used, the operation appears to be more like a transit time oscillator in that the frequency is critically related to the period. The output and efficiencies are usually intermediate between that of the negative resistance mode and the transit time mode of the two-plate construction, although some writers have reported very high efficiencies.

Herriger and Hulster[27] have published the most extensive experimental data on the four-plate tube. Fig. 14 shows their curve of efficiency *versus* electron orbits per period similar to that shown for the two-plate tube. The first maximum near the "order" two represents the usual operation condition for the tube, in which case the tube appears to be operating in the transit time mode. Where the number of orbits per period is very large, the oscillations can probably be explained on the basis of static negative resistance. It is interesting to note that for usual operating conditions the field strength required is approximately one-half that required by a two-plate tube operating in the negative resistance mode at the same wave-length.

In general, it can be said about the four-plate tubes that in the present state of development they are not capable of generating any shorter wave-length or higher power than can be obtained with the simpler two-plate construction. However, the high efficiencies reported are encouraging and it is probable that this tube will find a useful application in generating frequencies intermediate between the two-plate transit time oscillator and the two-plate negative resistance oscillator.

IV. Miscellaneous Problems

In presenting a fair picture of the present status of the magnetron oscillators, it is necessary to consider several factors which tend to limit their successful operation and useful application. These factors can be listed as follows:

(1) Filament bombardment
(2) Modulation
(3) Frequency stability
(4) Magnet requirements

The filament bombardment effect has been reported by a number of the magnetron investigators[14, 16, 25, 30] and is generally regarded as one of the most serious limiting factors, particularly in negative resistance magnetrons, when attempts are made to obtain very high power. This phenomenon exhibits itself by an increased heating of the filament which results in an unstable condition and a shortening of the life of the tube. Several good papers on this effect have appeared recently in the journals of the U.S.S.R.[31, 32] A rather complete investigation of this problem has also been made by Linder.* There are a number of opinions as to the physical nature of this effect and the question is still unsettled. However, it has been shown rather conclusively that the effect can exist with or without oscillations and that it is due to bombardment of the cathode by charged particles either positive ions, electrons, or both. Although this problem now appears as a serious limiting factor, there seems to be some hope for its solution. Megaw[29] and Ladner[24] have proposed the use of an auxiliary electrode for protecting the filament, and others are attempting filament stabilization methods.

The practical utilization of any high frequency generator for communication purposes depends upon the possibility of its being modulated. The magnetron in both its forms offers certain problems in modulation that are not present in conventional oscillators. The oscillation voltage of the negative resistance magnetron is a nonlinear function of the plate voltage, often being discontinuous at some points. This makes it impossible to use simple plate voltage modulation. Transit

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* E. G. Linder, "Excess energy electrons and electron motion in high vacuum tubes." Paper submitted to the Institute of Radio Engineers for publication.

time tubes do not exhibit this difficulty but they do show appreciable frequency change with plate voltage. These problems will require further research before they are completely solved, but already considerable progress has been made.

Von Lindern[23] has described a method of modulating magnetrons in which the carrier amplitude remains constant but is keyed on and off at an intermediate frequency. Modulation is obtained by varying the portion of the intermediate frequency period during which the carrier is on. Another interesting method reported by Linder and Wolff[19] is the use of an ionized gas modulator which modulates the radiated output from a beam transmitter. Modulation by means of an auxiliary electrode has been investigated by Groszkowski and Ryzko[26] and others.

The frequency stability of the present magnetrons leaves something to be desired, but it does not appear that the negative resistance type at least is inherently more unstable than a negative grid oscillator. The transit time oscillator which depends upon electron transit time requires extremely well-regulated voltages and a very constant magnetic field. Recently, Megaw[29] has reported frequency stability with a transit time magnetron sufficient to give an audible beat note between two oscillators operating above 1000 Mc.

The magnetic field power and size of electromagnet are often used as objections to magnetron generators. However, with magnet steels now available permanent magnets can be used for many applications where the power in the magnet is a limitation; and by proper design, the size of electromagnets can be made small compared to the whole equipment except at extremely high frequencies. An illustration of the relatively small size of magnet required for the 9 cm end-plate magnetron can be had from Fig. 15 which shows a 9 cm beam transmitter.[20]

V. Conclusions

To sum up the present status of magnetron oscillators the following statement can be made: In one mode of operation where the oscillations depend on a static negative resistance, the magnetron offers a means of generating larger amounts of power at wave-lengths below 100 cm than can be generated by any other type of vacuum-tube generator at the present time. In another mode where the oscillation mechanism depends upon electron transit time, the magnetron offers a means of generating the shortest continuous radio waves.

The negative resistance magnetron is particularly useful in the range of wave-lengths extending roughly from 100 cm to 30 cm. Radiation cooled tubes of this type are capable of generating power of the order of 50 watts at a wave-length of 50 cm, and special water cooled tubes can deliver more than 100 watts output, at the same wave-length.

The transit time magnetron is useful in generating high frequency currents at wave-lengths below 30 cm. Power outputs of a few watts can be generated at wave-lengths around 10 cm and detectable currents can be generated at wave-lengths as short as a few millimeters.

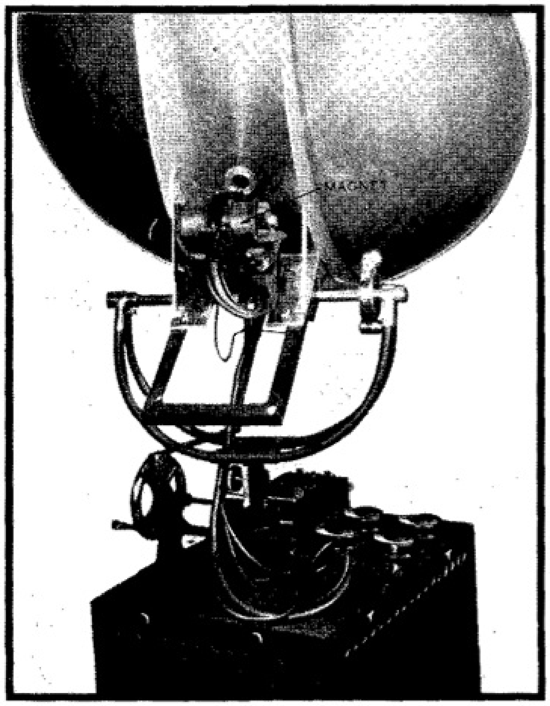

FIG. 15. 9 cm magnetron beam transmitter showing relatively small size of electromagnet.

In spite of certain factors that at present tend to limit the operation of the magnetron, it has already proved to be a useful tool in the exploration of the ultra-high frequency region. With the active development which this type of generator is undergoing, it may be expected to find many practical uses in the future.

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