WS No. 19 Mark III

THE MAGNETRON VALVE

GENERAL PRINCIPLES

Limitations of normal valve circuits

1. Normal valve circuits are not satisfactory for use at wave-lengths under about one metre and are quite impracticable in the centimetre range (λ of the order of 10 cms.). Not only is the construction, from lumped impedance, of a circuit to resonate at 3,000 Mc. extremely difficult, but valve constants render normal valves incapable either of generating or of amplifying such fre-'⁀ncies.

2. The low performance of normal valves is due to three main causes, viz. :—

(*a*) valve lead inductances.

(*b*) inter-electrode capacitances.

(*c*) transit-time effects.

3. The combination of (*a*) and (*b*) might produce an oscillatory circuit which would entirely mask the effect of any external tuned circuit. Cathode lead inductance produces an effective grid input resistance which is inversely proportional to the frequency squared. Anode and screen lead inductances are found to give rise to instability.

4. (*a*) The most serious consideration is, however, the transit-time effect. At frequencies of the order of 3,000 Mc. the transit-time, i.e., the time taken for the electron to '⁀vel from the cathode to the anode under the influence ⌞. ⌞he anode voltage, can be shown to be of the same order of magnitude as the periodic time of the oscillations. This leads to a very low grid input resistance, again inversely proportional to the square of the frequency. Table 1 shows approximate values of grid input resistance for a Mullard EF 50 at various total valve currents.

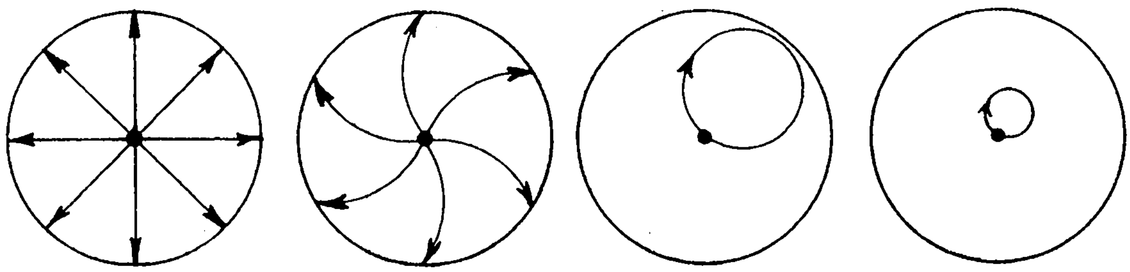
	Grid input resistance		
Frequency	Valve current 2Ma	Valve current 5Ma	Valve current 10Ma
20 Mc.	125k Ω	100k Ω	60k Ω
50 Mc.	25k Ω	14k Ω	10k Ω
100 Mc.	6.3k Ω	3k Ω	2.5k Ω
200 Mc.	1.5k Ω	0.8k Ω	0.65k Ω
500 Mc.	0.25k Ω	0.16k Ω	0.10k Ω

Table 1. Grid input resistance, at various frequencies, of a Mullard EF 50 valve

The grid input resistance becomes so low at ultra-high frequencies that the damping on the previous stage reduces its gain to less than unity. At these frequencies, normal valves cannot, therefore, be used as amplifiers.

(*b*) In addition to the low grid input resistance, there is a phase difference between the input to the grid and the anode output, due to the finite transit-time from grid to anode. This phase difference is dependent upon the anode voltage. The difficulty of feeding energy back into the grid circuit from the anode circuit, together with the low grid input resistance, makes the normal valve highly unsatisfactory as an oscillator.

5. The original types of oscillator used for the generation of U.H.F. waves were the Barkhausen-Kurz positive-grid oscillator and the magnetron. The latter has been developed in recent years and forms one of the fundamental valves used in centimetric technique.



T A-012 / 1-1 (a) (b) (c) (d)

Fig. 1. Electron paths for various magnetic field strengths

The diode in an axial magnetic field

6. As a preliminary to the study of the magnetron, consider a cylindrical diode with a thin cathode at the centre and a magnetic field along the axis. Let the anode potential be V, the magnetic field strength H, and the radius of the anode *a*.

7. Under the combined influence of the magnetic and electric fields, the path of the electron will be curved. If the space charge be neglected, it can be shown that the path is circular and, for a given voltage, that the radius will be inversely proportional to H.

Fig. 1 shows the electron paths for various strengths of the magnetic field. In Fig. 1 (*a*) the magnetic field strength is zero and the electron paths are radial. Fig. 1 (*b*) shows the bending due to a small magnetic field ; here the diameter of the circular electron path is greater than the anode radius. The effect of very high magnetic field is shown in Fig. 1 (*d*). There is obviously a critical value of the magnetic field at which the electron just misses the anode. Variations of the magnetic field near this critical value will produce large variations of anode current ; if the critical value is exceeded, the current will drop to zero (Fig. 1 (*c*)).

8. The value of the critical or cut-off field H*c* depends on the anode radius and voltage and is given by the equation,

$$Hc = \frac{6.72\sqrt{V}}{a} \text{ gauss}$$

where V = anode volts
a = anode radius in cm., assuming that it is large compared with the filament radius.

9. (*a*) The above arguments presuppose the absence of space charge near the cathode. In practice, this condition exists only when the valve is first switched on. Under normal conditions of operation, space charge will be present and this modifies the circular path as in Fig. 2.

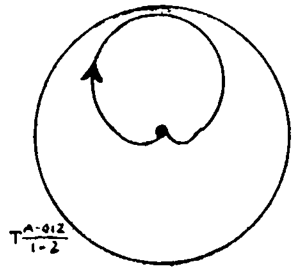


Fig. 2. Electron path neglecting effect of magnetic field on space-charge distribution

(*b*) If the effect of the magnetic field on the space charge is taken into account, the picture is still further modified. Fig. 3 shows a comparison of the two cases. Curve 1 is the path neglecting the effect of the magnetic field upon the space charge distribution, while curve 2 takes it into account.

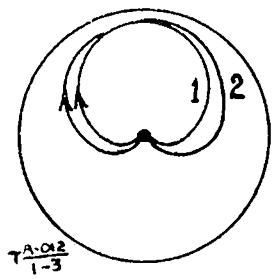


Fig. 3. Electron paths compared, with and without consideration of effect of magnetic field

10. Figs. 4 and 5* respectively show curves of plate current against magnetic field (voltage constant) and plate current against anode voltage (magnetic field constant).

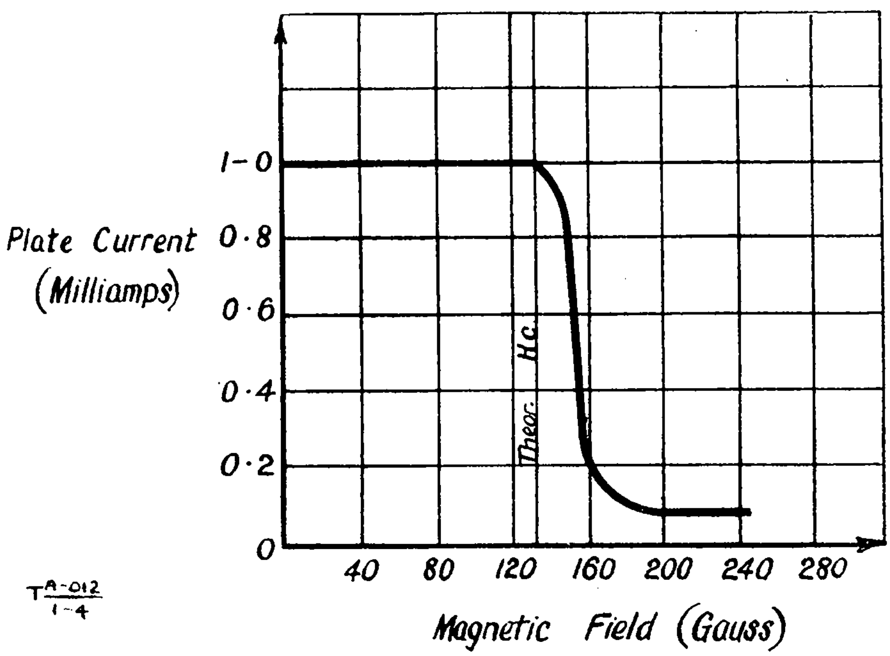


Fig. 4. Curves of plate current against magnetic field strength, with plate voltage constant

*Figs. 4 and 5 from "*Thermionic Tubes at Very High Frequencies*," by A. F. Harvey. Chapman & Hall, 1941

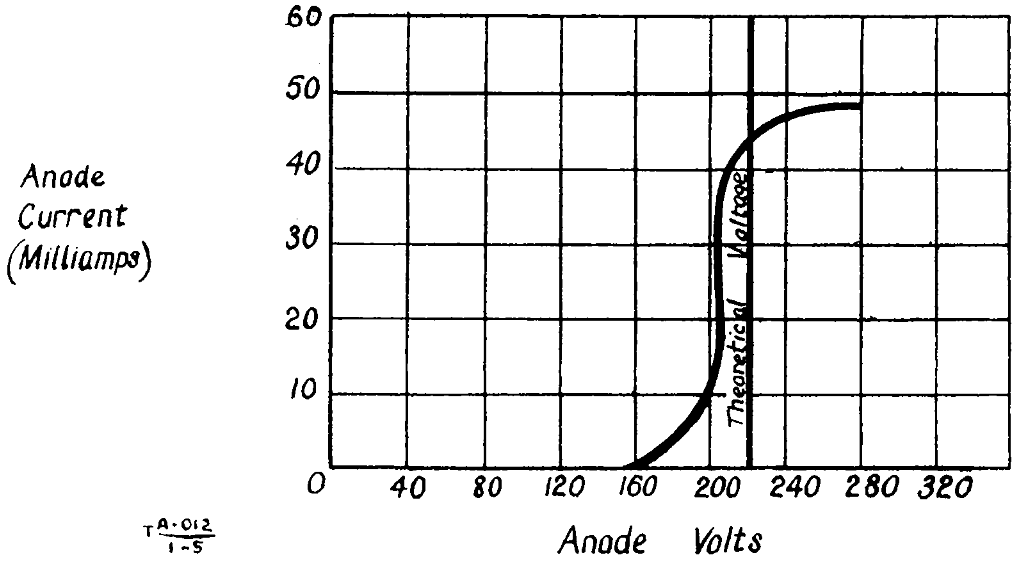


Fig. 5. Curves of plate current against plate voltage with magnetic field strength constant

11. It will be noticed that there is a discrepancy between the cut-off field calculated and that which is found and that there is a considerable rounding both at the onset and the end of the drop in anode current. There are various causes for this :—

(*a*) Inaccuracy in lining up the magnetic field along the axis of symmetry of the diode. This is highly important and the effect of tilt of field is shown in Fig. 6.

(*b*) Eccentricity of the cathode has a large effect and is obviously linked up with (*a*).

(*c*) The presence of high frequency oscillations of small amplitude has considerable effect.

(*d*) The different emission velocities of the electrons from the cathode have a small effect.

(*e*) A second order effect is due to the voltage drop along the filament.

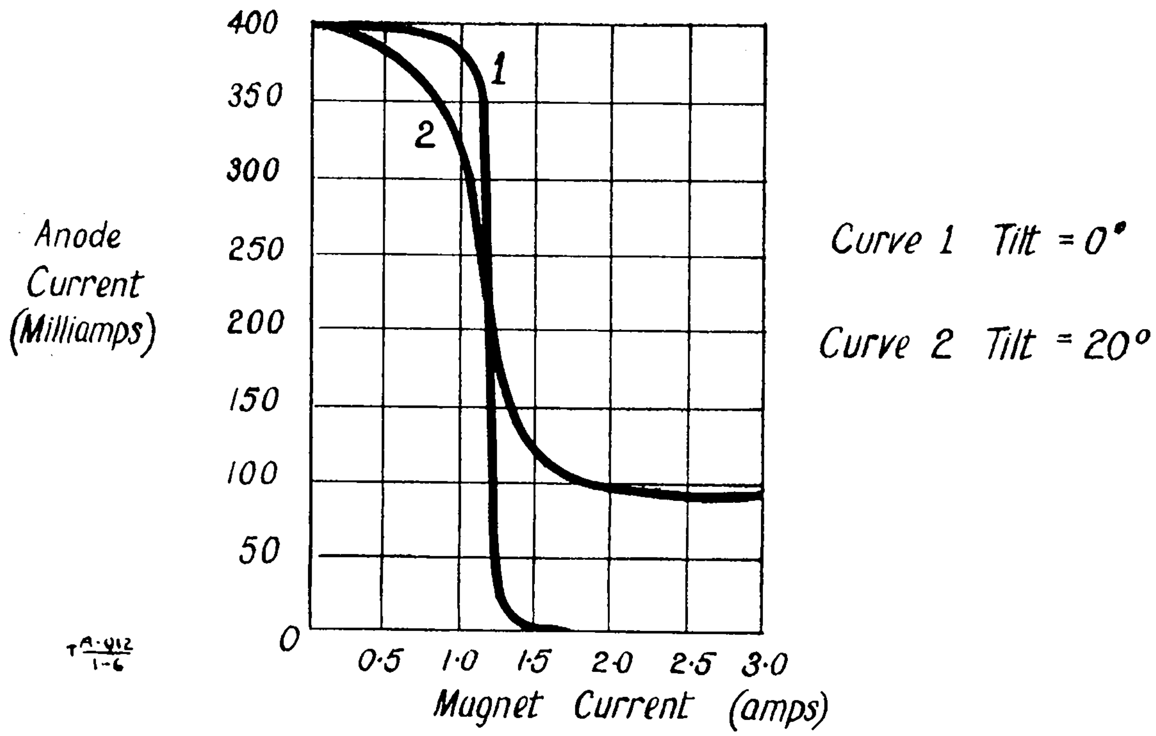


Fig. 6. Effect of tilt of magnetic field on characteristics

The split-anode magnetron as an oscillator

12. It has been found that a cylindrical diode having its anode split into two or more segments can function as an oscillator under the influence of an axial magnetic field. The modes of oscillation fall into three main divisions, which can be summarised as follows :—

(*a*) *The dynatron mode.* The magnetic field required is equal to, or greater than, cut-off. The wave-length is dependent on the external tuned circuit and is dependent on the dimensions of the tube and of the electric and magnetic fields. The only frequency limit is the upper one ; it is necessary that the periodic time be much greater than the electron transmit-time.

(*b*) *The resonance mode.* The magnetic field required is greater than cut-off. The wave-length is substantially independent of the external circuit and is a function of the tube dimensions and field strength. The wave-length is proportional to the magnetic field for a given tube and anode voltage. Wave-lengths range from 10 cm. to indefinitely long wave-lengths.

(*c*) *The electron mode.* The magnetic field must be near cut-off. The wave-length is independent of external circuits and is usually less than 15 cm. Wave-length is inversely proportional to magnetic field.

The dynatron mode

13. (*a*) Consider a cylindrical diode in the presence of an axial magnetic field as before, but let the anode be split into two parts A_1 and A_2 (Fig. 7). Let A_1 be at voltage V and let A_2 be at zero potential, while the magnetic field is such as to cut off the anode current if both segments were at V. The electrostatic field opposes the deflecting effect of the magnetic field and causes a large current to flow to A_1 but only a small (almost zero) current to flow to A_2 (Fig. 7A). Now, as the voltage on A_2 is increased, the electrostatic field becomes less operative and more current flows to A_2 at the expense of the current in A_1 (Fig. 7B). When the voltage on A_2 approaches that on A_1 the current in both anodes starts to fall rapidly, since the system is approaching the cut-off condition. The current on both anodes will be zero when A_2 is at voltage V (Fig. 7C). Further increases in the voltage of A_2 will serve to increase the current to both anodes, since the magnetic field becomes insufficient to maintain the

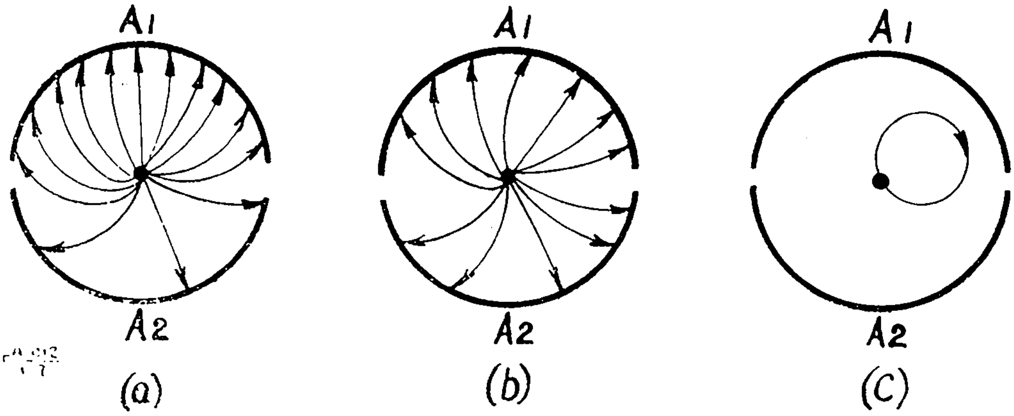


Fig. 7. Electron paths in split-anode magnetron

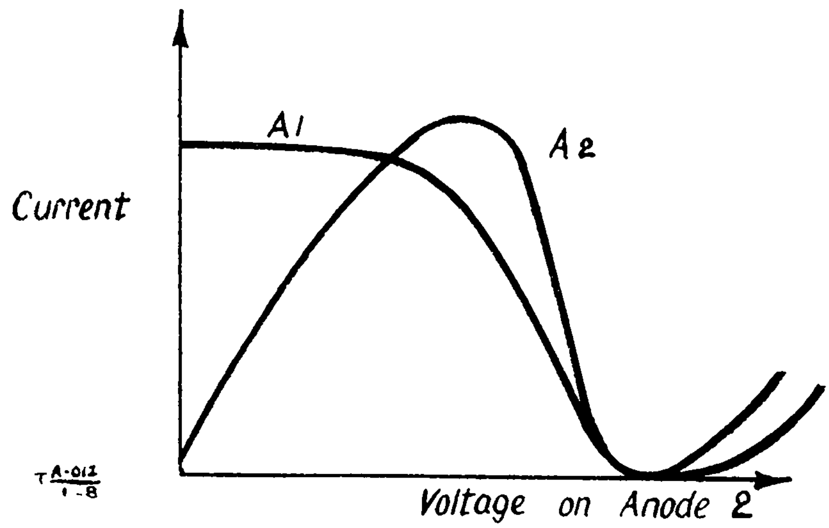


Fig. 8. Curves of plate currents against plate voltages

cut-off conditions. It is, however, obvious that A_2 will now draw the larger current, since it is at the higher potential. Fig. 8 gives a schematic representation of the currents to be expected.

(*b*) There is a region of negative resistance where increase in anode voltage causes decrease in current near the critical value of voltage. In Fig. 9 curves are given showing how the currents in the two segments vary as either anode is varied about a mean for two different values of magnetic field.

It can be seen that, within limits, the current flowing to the segment at the lower potential is greater than the current flowing to the segment at the higher potential. The range of this negative resistance region is increased by using a higher value of magnetic field.

(*c*) Any tube which has negative resistance properties is capable of functioning as an oscillator when connected to a tuned circuit of sufficient dynamic resistance. The circuit of Fig. 10 will then function as an oscillator, the peak-to-peak voltage being such that the anode voltage swings within the negative resistive range.

(*d*) With a high value of magnetic field, current will flow only on the peaks of the oscillation and the magnetron acts as a class C push-pull dynatron oscillator. The ordinary treatment of a dynatron oscillator can be applied to this type of circuit.

(*e*) The efficiency of this long-wave dynatron mode of the magnetron is rather less than that of a tetrode of the same anode voltage and filament emission ; it falls almost to zero when the electron transit-time becomes comparable with the periodic time of the oscillation to be maintained.

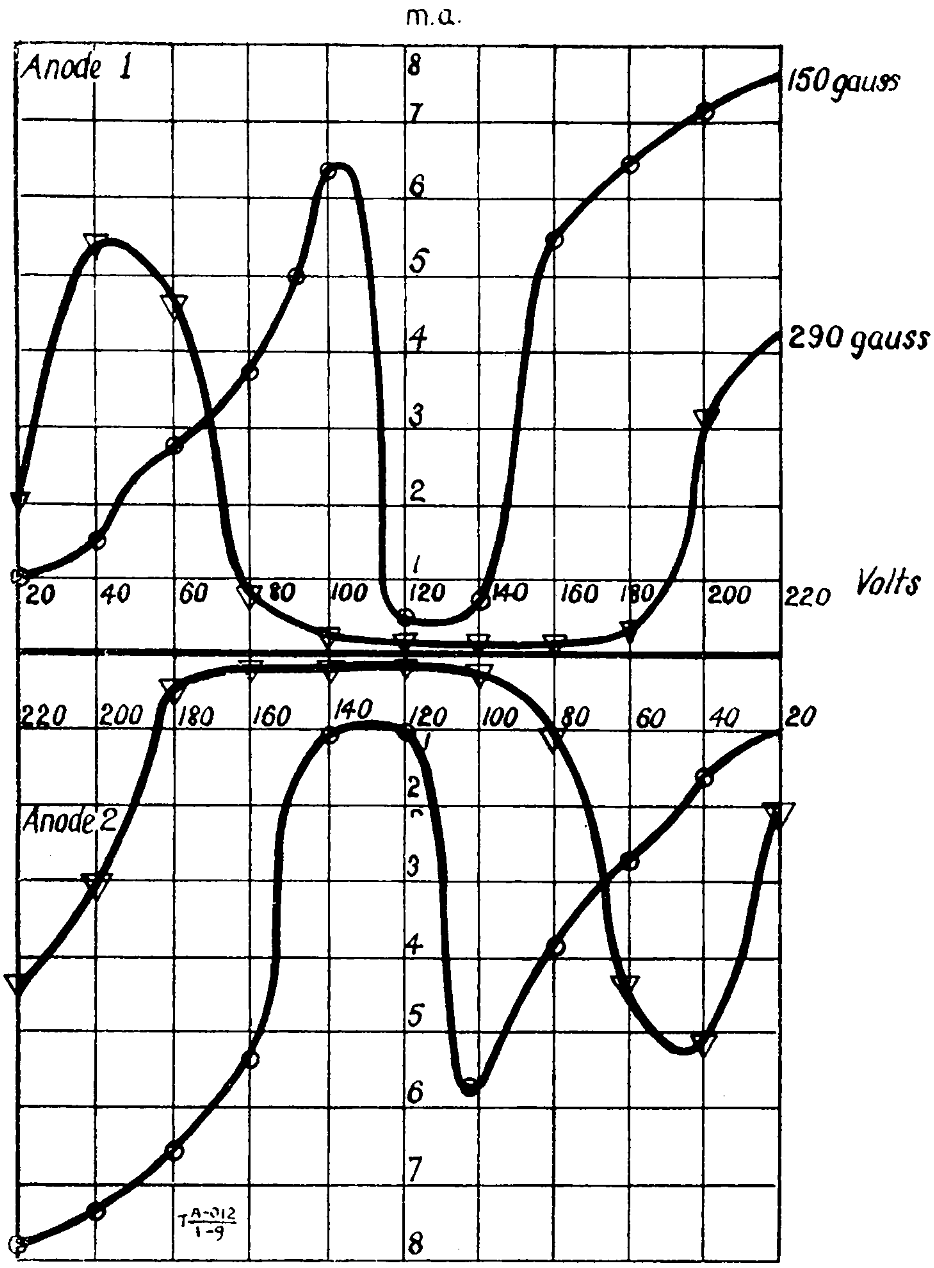


Fig. 9. Curves of plate currents against variations in plate voltages and magnetic field strength

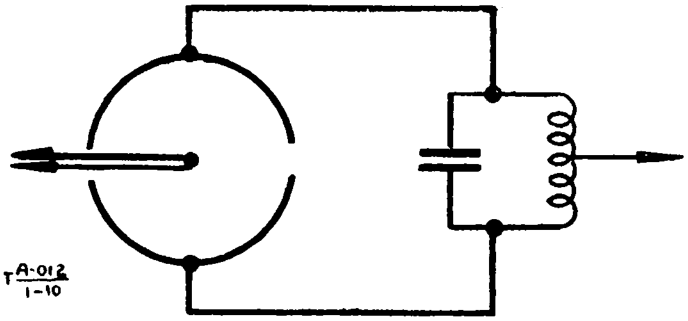


Fig. 10. Split-anode magnetron connected as an oscillation generator

(*f*) It is to be noted that the values of the electric and magnetic fields required do not depend on the frequency to be generated ; thus, provided that the magnetic field is equal to or greater than cut-off, any frequency can be maintained, subject to the higher limit already quoted, without alteration of field strengths.

The resonance mode

14. (*a*) For values of magnetic field greater than cut-off, a type of oscillation occurs in which the wave-length is not very dependent upon the constants of the external circuit. This is quite clearly due to causes different from those just described in the dynatron mode. The wave-length is actually dependent on the field strength, and for any given set of conditions :—

$$\omega = \frac{2Vk\ 10^8}{a^2\ H}$$

where $\omega = 2\pi\ f$ (f = frequency)
V = mean anode voltage
H = magnetic field
a = anode radius
k = number of pairs of segments.

The formula gives the optimum wave-length for the conditions and only a small variation can be made, by detuning the external circuit, without causing the oscillations to cease. For any given magnetron :—

$$\frac{\lambda\ V}{H} = \text{constant}$$

where λ = wave-length.

(*b*) Wave-lengths from the order of 10 cm. up to indefinitely long wave-lengths are obtainable.

(*c*) In a cylindrical magnetron, most of the voltage drop occurs near the filament and only a small residue spreads across the space to the anodes. The motion of the electrons in the field has been the subject of much study. It is suggested that if the anodes are subjected to an alternating voltage $V - v \sin \omega t$, then an electron passing one of the gaps will suffer deflection towards the anode at the lower potential. If this has the effect of causing the electron to hit that anode, the dynatron oscillation occurs. If, however, the deflection is insufficient for this, the electron will carry on along its path towards the cathode ; but, instead of reaching the cathode, the deflection suffered will cause it to miss the cathode and a type of curved cycloidal path will be followed. Provided the alternating anode voltage is of the correct frequency, then at each passage past a gap the electron will suffer a further deflection and deceleration until it ultimately hits one of the anodes (Fig. 11).

(*d*) Support for this theory is given by G. R. Kilgore, who, by using a magnetron with a small amount of residual gas present, was able to photograph the ionisation track left in the path of the electron.

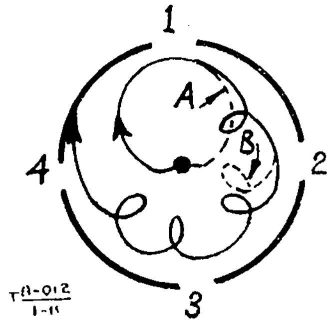


Fig. 11. Cycloidal electron path with alternating voltage applied to anodes

The dotted lines in Fig. 11 show the path the electr would have taken had it not been deflected by gap 1 (A) and subsequently by gap 2 (B).

(*e*) Measurements made on a magnetron when oscillating in this mode showed that a resonant condition existed in the tube, which had the usual features of a series circuit, but with component impedances consisting of negative resistance, negative inductance and negative capacitance, giving rise to the name " resonance mode."

(*f*) From the formula $\omega = \frac{2Vk\ 10^8}{a^2\ H}$ it is seen that the wave-length is proportional to the square of the anode radius and inversely proportional to the number of segments. Thus, for ultra-short wave-lengths, a small diameter anode cut into a large number of segments is needed. The consequent limiting of the permissible dissipation makes the tube capable of handling only small powers.

The electronic mode

15. (*a*) This mode is characterised by the generation of a wave-length that is closely related to the electron transit-time and is practically independent of external circuit constants. Wave-lengths obtainable in this mode is usually less than 15 cm. and occur in the neighbourhood of the critical magnetic field. Experiment has shown that wave-length is approximately given by the formula :— $\lambda H = 11{,}000$. This is in close agreement with the assumption that the oscillations have a periodic time equal to twice the calculated transit-time of an electron from cathode to anode.

(*b*) In general, it is found that the angle between the magnetic field and the electrode axis is critical and is not zero. The width of the anode gaps has no important effect on efficiency, which is greatest with small anode currents and falls rapidly when the space charge density becomes large. This suggests that it is not the arrival of electrons at the anode, but the transfer of energy from the electrons to the circuit during transit, that determines whether or not oscillations can be maintained.

(*c*) From the above facts it is possible to form an explanation of how the oscillations are maintained. Since the width of the gaps has no effect, the case of a cylindrical diode having a voltage just less than the critical value can be considered, so that, for a steady anode voltage the electron path will be a circle (Fig. 12A). It should understood that, in practice, the anode will always be split into two or more segments to enable a tuned circuit to be incorporated.

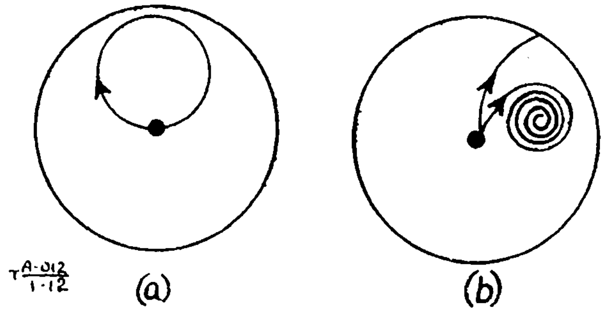


Fig. 12. Electron paths with critical anode voltages

(*d*) Now consider that an alternating potential of the electronic frequency is superimposed on the D.C. anode potential. An electron which leaves the cathode during the first part of the positive half-cycle will receive a little extra rgy and will hit the anode, where its energy is dissipated as heat. An electron leaving the cathode about a half-cycle later, when the anode is going negative, will give up energy to the anode circuit, for, whether it be approaching the anode or receding from it, the anode alternations are always such as to oppose the radial motion of the electron. The electron path becomes a closing spiral. As the spiral gets smaller the electron circle takes place more and more in the region of almost constant potential near the anode and its rotation frequency increases. Thus, the phase of the useful group of electrons relative to the alternating anode voltage changes continuously until, instead of giving up energy to the alternating circuit, the electrons start to abstract energy, with a consequent opening of the spiral, until they reach the anode with almost their original velocity. The net output will therefore be very small.

(*e*) The effect of tilting the magnetic field is to pull the spiral out to a helical path, of which the axis tends towards the anode, along the magnetic field. If the tilt is critically set, the electrons can be made to hit the anode just as their period of usefulness is over, thus giving optimum efficiency. The tilt of the field has also the effect of eliminating unired long-wave oscillations of the other modes. The optimum tilt depends on the filament emission as shown in Fig. 13 for a typical magnetron.

(*f*) The magnetron in the electronic mode is capable of producing extremely short wave-lengths, although power output and efficiency are low. The optimum anode voltage and filament emission increases with frequency; thus, the wave-length is limited by the allowable dissipation.

Frequency drift in the electronic mode

16. (*a*) Frequency drift in the magnetron is due to :—

- (i) Temperature changes as the valve warms up after switching on.
- (ii) variation of anode and filament voltages consequent on mains supply fluctuations.

(*b*) The greater part of the drift due to temperature changes occurs during the first two minutes, after which the frequency is within 2 Mc. of its final value. After a further ten minutes the frequency is within 1 Mc. of its final value.

(*c*) Frequency change with filament voltage is negligible within quite wide limits of variation of the heating voltage (Fig. 18).

(*d*) The drift with anode voltage is considerable, although the drift decreases as the loading of the H.F. circuit increases. It is, however, possible to choose a voltage (Fig. 17) such that a small fluctuation of mains voltage causes only a small frequency variation. In general, a fairly well stabilised supply is satisfactory.

Conclusion

17. It has been assumed throughout that an external tuned circuit is attached to the anodes, but this is not always so. It is possible to choose the dimensions of the anode, as regards length, radius, and distance apart of the segments, so that the whole anode system is the resonant circuit and no external circuit is then necessary. Each pair of anode fingers can be considered to form a section of transmission line, short-circuited at one end, behaving as quarter-wave resonators. This gives rise to the term "resonant segment magnetron." Fig. 14 shows a diagrammatic sketch of the G.E.C. magnetron, type E.1210B, which is fitted with a standard octal base. Figs. 15 to 18 show the effect on wave-length of the variables. The curves refer to the electronic mode. The discontinuity in Fig. 15 is due to a change of mode of oscillation of the lechers.

18. As yet there is no complete theory to explain all the phenomena associated with the magnetron, but there is some evidence that the modes of oscillation are not so sharply defined as this treatment suggests.

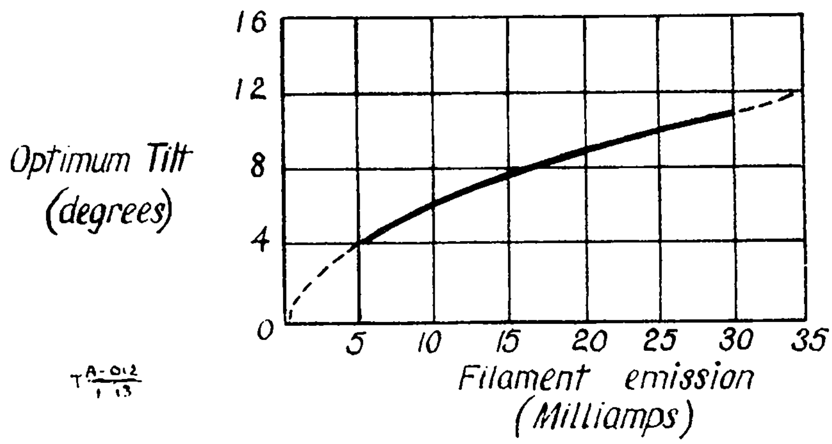


Fig. 13. Effect of tilt of field on emission

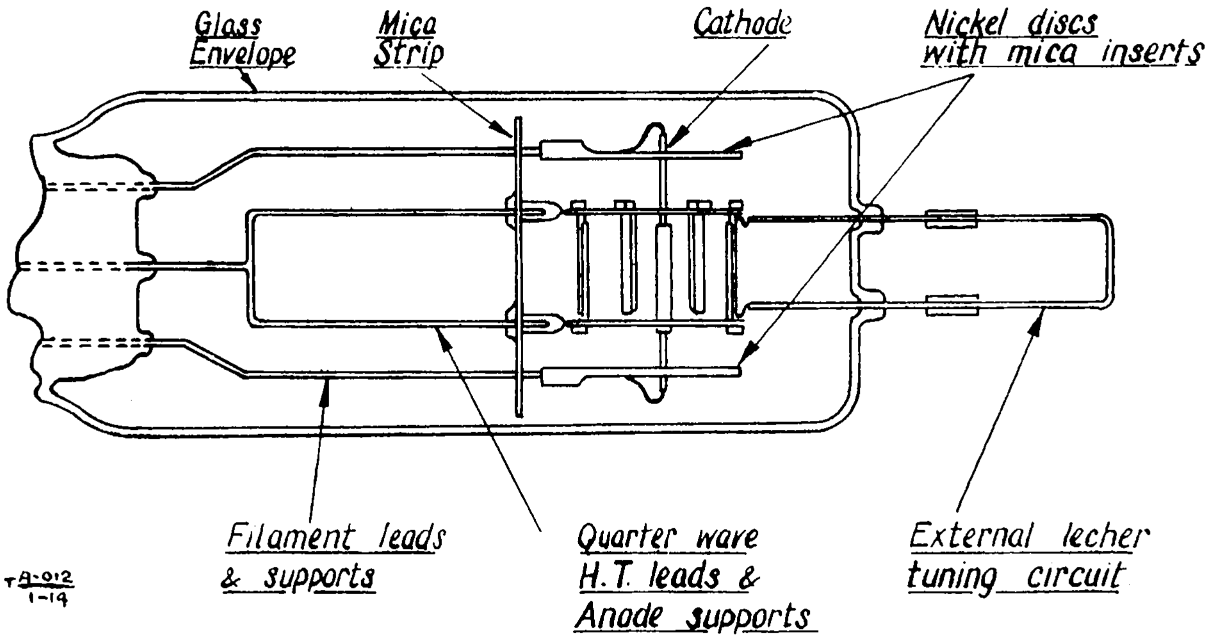


Fig. 14. Structure of G.E.C. magnetron, type E.1210B.

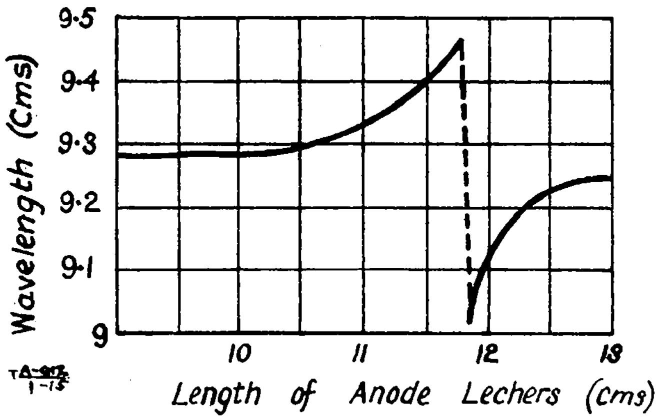


Fig. 15

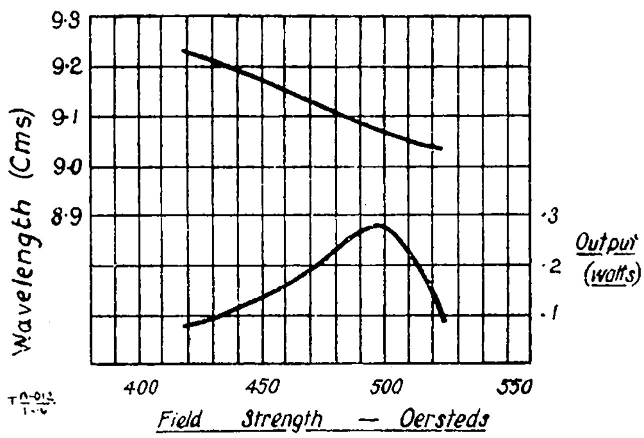


Fig. 16

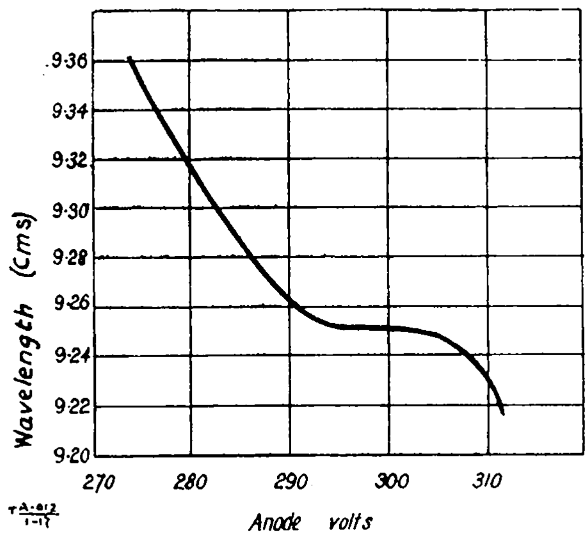


Fig. 17

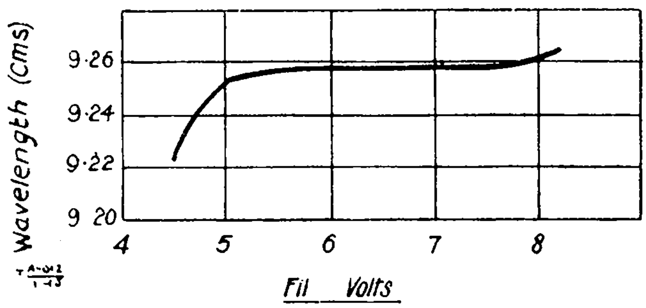


Fig. 18

Figs. 15—18. Effects of variable factors on wave-length generated

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