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SOME PROPERTIES OF MAGNETRONS USING SPATIAL-HARMONIC OPERATION

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SUMMARY

To reduce the problems involved in the design of magnetrons of low voltage and power for operation at frequencies of the order of 10 000 Mc/s and higher, a system is proposed in which the anode has only a few gaps, e.g. two or four. Operation at low anode voltage and magnetic field is achieved by electron interaction with the Fourier space components of the field.

A convenient and simple embodiment is described, and factors likely to result in operation different from the conventional multiple-circuit magnetrons are analysed briefly. In particular, the modes of oscillation and the magnitudes of the components of the different possible spatial harmonics are discussed for two types of anode circuit.

Details of operation of valves using both types of anode with two and four gaps are given, and comparisons are made where appropriate with the earlier analysis. The simple electrical structure of the two-gap anode enables a useful tuning range to be obtained by external-circuit adjustment, and some details of tuning performance are given.

The paper concludes with comments on noise performance and speed of build-up of oscillations.

LIST OF SYMBOLS

N = Number of resonant circuits.
ω = Angular frequency.
V_{min} = Theoretical minimum voltages for oscillation.
a = Anode radius.
b = Cathode radius.
r = A radius between a and b.
e = Electron charge.
m = Electron mass.
n_0 = Fundamental mode number due to fields in N cavities.
n = Component mode number.
μ = An integer.
θ = Angular position relative to "A" symmetry axis.
θ_s = Angular width of slot.
ϕ = Angular spacing between gaps 1 and 2 in m.s. anode.
K = $2\pi/2\phi$.
E = Electric field in resonator gap.
E_a = Total electric field at anode surface.
E_n = Electric field of component n.
V = R.F. voltage across gap.
I_S = Anode current for start of oscillations.
I_F = Anode current for finish of oscillations.
Q_0 = Q-factor of unloaded valve anode circuit.
Q_E = Q-factor of loaded valve anode circuits assuming $Q_0 = \infty$.
Q_L = Q factor of loaded valve anode circuit.

(1) INTRODUCTION

The use of the multiple-circuit magnetron to generate a few watts of continuous-wave power at wavelengths of the order of 3 cm involves a design of valve which is difficult to construct where the voltage is less than 1 000 volts, owing to the need both for small resonant circuits with narrow anode gaps and for an accurately central cathode. Such a valve having N resonant circuits, where N may be in the range 18–24, is usually designed for operation in the π mode, i.e. with a phase difference of π between the voltages across successive gaps. Continuous interaction takes place between the rotating electron cloud and that rotating-wave component of field present at the anode having the velocity $\omega/\frac{1}{2}N$, which is the fundamental of the infinite series of waves into which the discontinuous field at the anode surface may be analysed.[1]

The theoretical minimum voltage V_{min} at which oscillations may be generated—although the efficiency is zero—is given by equating the potential energy of an electron leaving the cathode with the kinetic energy of the electrons arriving at the anode, which are assumed to have the velocity of the field with which they are interacting. Thus

$$eV_{min} = \frac{1}{2}m(\omega a/\tfrac{1}{2}N)^2$$

In practice, a voltage about twice the value given by this expression needs to be used if good efficiency is to be obtained. It then follows that for fixed anode voltage, efficiency and anode radius the number of circuits must be increased in proportion to frequency. Further, for fixed anode voltage and frequency, change of number of circuits does not result in any change in the spacing between segments, or in segment gap-width. Finally, with increase in frequency and fixed number of segments and voltage, the gap width must decrease.

The need to increase the number of segments, and to reduce the gap width as the frequency is increased, introduces serious difficulties. Increase in number of segments and resonant circuits adds to the number of possible modes of resonance of the anode system and results in increased problems in ensuring satisfactory stability of operation in the required mode of resonance of the anode system. Reduction of gap width and segment width brings in mechanical difficulties of construction, together with problems of heat dissipation.

The question which has frequently been asked is whether these difficulties could be minimized by the use of Fourier space components of the travelling wave with which the electron stream interacts. Simple analysis shows that if the circuits of a multiple equal-cavity magnetron are excited at the frequency of one of the resonant modes, so that the pattern of the electromagnetic field within successive cavities is repeated n_0 times around the circumference, the electromagnetic wave within the interaction space between the anode surface and the cathode is composed of an infinite series of components. This arises from the discontinuous changes in electric field which take place at the anode surface owing to the presence of the metal segments of finite width. In an equal-cavity system these components have numbers $n_0 \pm \mu N$, μ being an integer. Putting $\mu = +1$ and $n_0 = \frac{1}{2}N$, corresponding to operation in the π mode, one component of this series is that having a mode number $n = 3N/2$, i.e. the same mode number as for a valve with $3N$ resonators instead of N. Thus, if the amplitude of the field of this component in the interaction space is sufficient, it should be possible to achieve operation by interaction with this component, with the advantage of the larger number of circuits but without the mechanical and electrical disadvantages.

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Experiments have been made to see whether operation of this type, requiring lower magnetic field and voltage, can be obtained, but so far as is known these have not been successful for valves having upwards of eight resonators with anode diameters in excess of $0 \cdot 1\lambda$. The lack of success in the cases so far tried may be ascribed to the rapid fall off of the amplitude of the desired component of the field away from the anode. Analysis shows that in the absence of space charge the amplitude of the tangential electromagnetic field at radius r is proportional to

$$(r/a)^{n-1}[1 - (b/a)^{2n}]$$

Thus, if n is large (it has a minimum value of 12 in the designs mentioned above) this field falls off very rapidly on leaving the anode surface. Consequently, it seems probable that in the cases so far investigated the magnitude of this field over the interaction space is too small to allow effective bunching of the electron stream to take place.

It was therefore decided to investigate the performance of valves particularly designed for this type of operation, where both the mode number of the wave component used and the anode radius were not too large, and the work described here is the outcome of this.

It was thought that if satisfactory operation could be obtained, it would lead to valves of relatively simple construction, and that, owing to the simpler resonance properties of the anode system, following the smaller number of resonant cavities used, it would be possible to achieve a useful tuning range by coupling the valve to a simple form of external-cavity tuner.

(2) DESCRIPTION OF EXPERIMENTAL VALVES

In the first place it was proposed to explore space-harmonic operation in an anode system which could be thought of as having 12 uniformly spaced resonators, eight of which had been omitted from the anode in two groups of four, and it was hoped to achieve operation by interaction between the electron stream and a component field in the interaction space having the same periodicity as that produced by the full number of resonators.

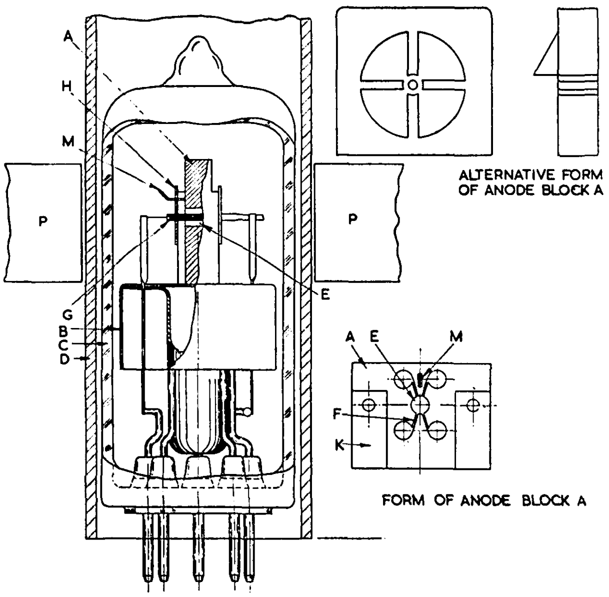


Fig. 1.—General arrangement of spatial-harmonic valve.

Fig. 1 shows the general form of valve used for these experiments. The anode system is formed in a thin block of copper, A, supported by a cup, B, within a glass bulb, C, fitting inside a circular waveguide, D. The anode system consists of a central hole, E, of diameter 2 mm having four resonant circuits of the hole-and-slot type arranged around it. Adjacent slots, F, which are long and narrow have their centre lines on diameters displaced by an angle of 30°, i.e. they have the spacing of a system of 12 slots, although eight of these are missing. This system was called the missing-segment system (abbreviated m.s.). It will be clear from inspection of the Figure, in which the proportions of the holes and slots are arranged for an oscillating wavelength of 3 cm, that it would, in fact, be impossible to accommodate the full number of circuits in the space available. In an alternative design a further two adjacent resonant circuits were omitted leaving only two remaining. A tubular cathode, G, is supported centrally within the anode hole by mica cards, H, attached to the raised portions, K, of the copper block, A. Projecting from the end of this block from the tongue formed by two adjacent slots is a small wire, M, through which power is radiated from the oscillating system into the waveguide formed by the surrounding close-fitting metal tube, D.

The top surface of the cup, B, forms the zero-potential reference surface of the whole oscillatory system, and the cylindrical portion forms with the outer tube a choke to prevent transmission of power downwards to the base of the valve. The base carries pins to which connections are made to anode, cathode and heater wires, and which carry a support for the whole oscillatory system.

Operation takes place with the valve and its surrounding circular waveguide placed in a magnetic field of direction parallel to the cathode axis and formed between the poles, P, of a permanent magnet.

After a number of experimental valves of this type had been made it became clear that difficulties were arising in repeatability of operation, owing to inaccuracies in construction arising from an inability to machine accurately the long narrow slots used in the design. The use of a system having the same limited number of circuits (four or two) with gaps which are, however, symmetrically placed around the anode surface was then considered. Such a system permits considerable simplification in the method of forming the anode (e.g. hobbing may be used) and results in a valve of relatively cheap but accurate construction.

Fig. 1 shows an outline of the anode of the 4-segment version of this valve, which is referred to as the symmetrical-anode type (abbreviated s.a.). Since the width of adjacent gaps is no longer geometrically limited to a value such that the wave transit angle $n\theta_s$ at the anode surface is of the order of $\frac{1}{2}\pi$ (as it was with the m.s. system), the opportunity may be taken to increase this to a value close to π. This change reduces the amplitude of the space component for a given gap voltage (it is proportional to $\sin \frac{1}{2}n\theta_s/\frac{1}{2}n\theta_s$), and consequently the circuit load impedance must be increased in order to give the necessary gap-voltage increase.

(3) ANALYSIS OF MECHANISM OF OPERATION OF M.S. VALVE

(3.1) Modes of Resonance

The anode circuits, when not coupled to a load, may be considered as a first approximation to behave as the ring of lumped circuits. Such a system has four modes of oscillation, although formally two of these modes are different components of a doublet mode.

The first, the π mode, for which there is a 2λ standing wave of potential around the anode, is one in which currents in adjacent cavities differ in phase by π, as indicated in Fig. 2(a).

The second and third modes, the $\frac{1}{2}\pi$ modes, are those for which there is only a single standing wave of potential, as indicated in Figs. 2(b) and 2(c) for the two possible axes of symmetry A or B of a loosely coupled driving source. This driving source might,

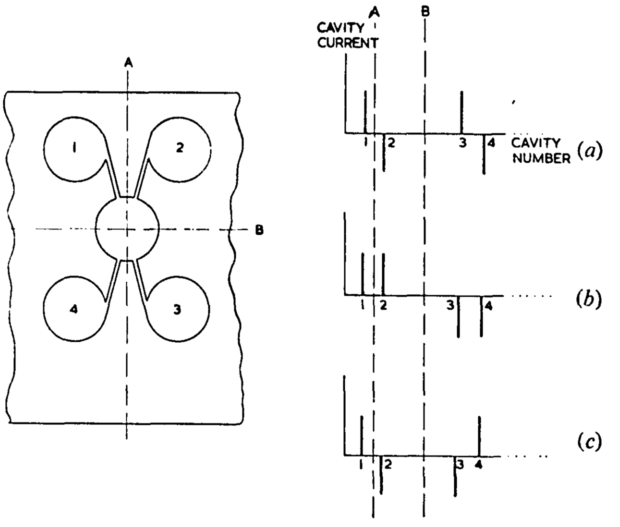


Fig. 2.—Distribution of current in m.s. anode.

(a) π mode.
(b) π/2 mode with A symmetry axis.
(c) π/2 mode with B symmetry axis.

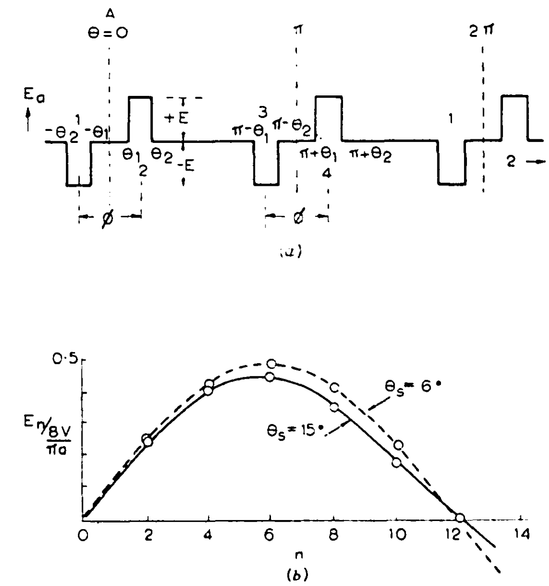


Fig. 3.—Field distribution and component amplitudes for π mode (m.s.).

(a) Field distribution.
(b) Component amplitudes.

for example, be a short probe of the type shown in Fig. 1, suitably excited.

The fourth mode is the zero mode, for which currents in all four cavities are in phase, and there are consequently large potentials across the segments of anode surface joining slots 2 and 3 and slots 4 and 1. The frequency of this mode is very high, with the small ratio between anode diameter and wavelength used in these valves, so that it may be ignored so far as operation is concerned.

In later work it was decided to eliminate two further oscillatory circuits, leaving only circuits 1 and 2 coupled to an otherwise plain anode. Only two modes of resonance are then possible, the π mode and the zero mode of much higher frequency.

(3.2) Analysis of Interaction Field

(3.2.1) Oscillation in the π Mode (Four Segments).

The total field present within the space between anode and cathode, arising from the fields present at the anode surface which are a consequence of the distribution of current in the resonant cavities discussed above, may be derived by Fourier analysis.

It can be assumed that, with the narrow gaps (in terms of oscillating wavelength) used in the design under discussion, and with the relatively large spacing between anode and cathode, the field at the anode is represented by the simple function shown in Fig. 3(a) when the anode is resonant in the π mode. Here the angular position $\theta = 0$ represents the axis of symmetry A of Fig. 2(a) and $\theta = \theta_1, \theta_2$ defines the position of the edges of the gap 2. The position of the edges of the gap 1 is defined by $\theta = -\theta_1, -\theta_2$. Gaps 3 and 4 are similarly placed round the line $\theta = \pi$. The spacing ϕ between the centre lines of gaps 1 and 2 and of 3 and 4 is set by the requirement $\phi \times 2K = 2\pi$, where K is an integer. Thus the spacing between near resonators is the same as it would be if $2K$ equally spaced resonators were used in the anode.

Fourier analysis of the field distribution having a peak value of $\pm E$ gives a total field at the anode surface

$$E_a = \frac{4E}{\pi}\sum_{n=-\infty}^{n=+\infty}\frac{\cos n\theta_2 - \cos n\theta_1}{n}$$

with the limitation that only even values of n are valid.

Inserting V, the r.f. voltage across the slots, the magnitude of the separate components is

$$E_n = \frac{8V}{\pi a}\left[\frac{\sin \frac{1}{2}n(\theta_2 - \theta_1)\sin \frac{1}{2}n(\theta_2 + \theta_1)}{n\theta_s}\right]$$

The variation of $E_n\pi a/8V$ with n is shown in Fig. 3(b) for the case

$$\tfrac{1}{2}(\theta_2 - \theta_1) = \tfrac{1}{2}\theta_s = 7 \cdot 5°, \tfrac{1}{2}(\theta_2 + \theta_1) = 15°$$

This characteristic shows a peak at $n = K = 6$, indicating that the component having the maximum amplitude is that which would also have maximum amplitude with $2K$ equally spaced gaps. The value of this maximum is

$$\frac{8V}{\pi a}\frac{\sin \frac{1}{2}n\theta_s}{n\theta_s}$$

The dotted curve shows the effect of reducing the slot width θ_s from 15° to 6° with the spacing of the slots unchanged.

(3.2.2) Oscillation in the π/2 Mode (Four Segments).

A similar analysis may be carried out for the two cases of oscillation in the $\pi/2$ mode, for which the field distributions are as shown in Figs. 4(a) and 4(b). The amplitudes of the separate components are now

$$E_{nA} = \frac{8V}{\pi a}\left[\frac{\sin \frac{1}{2}n(\theta_2 - \theta_1)\cos \frac{1}{2}n(\theta_2 + \theta_1)}{n\theta_s}\right]$$

for symmetry relative to the line A and

$$E_{nB} = \frac{8V}{\pi a}\left[\frac{\sin \frac{1}{2}n(\theta_2 - \theta_1)\sin \frac{1}{2}n(\theta_2 + \theta_1)}{n\theta_s}\right]$$

for symmetry relative to the line B. In both cases only odd values of n are permissible.

Values of the amplitudes of these components are shown in Fig. 4(c) for $\theta_s = 15°$.

(3.2.3) Oscillation in the π Mode (Two Segments).

In the case of two segments, only the π mode is of interest, and for this the total field is just half that for the π mode with four segments, but now all values of n are present.

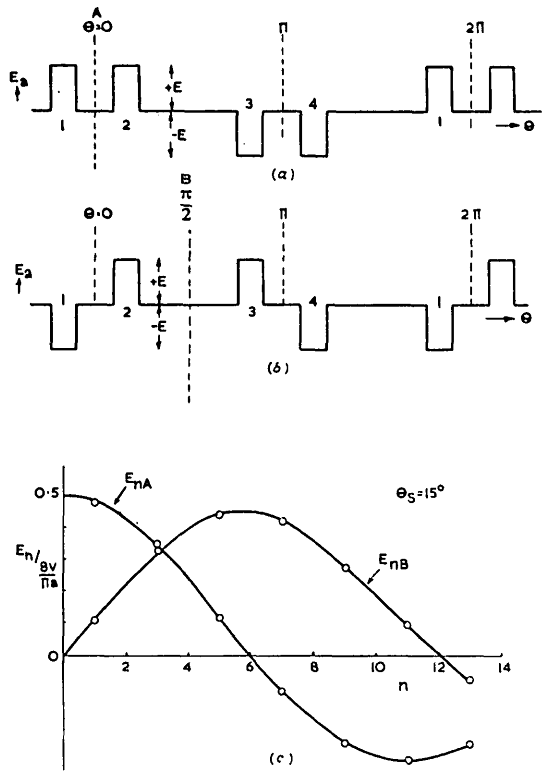


Fig. 4.—Field distribution and component amplitudes for $\pi/2$ mode (m.s.).

(a) Field distribution; A symmetry.
(b) Field distribution; B symmetry.
(c) Component amplitudes.

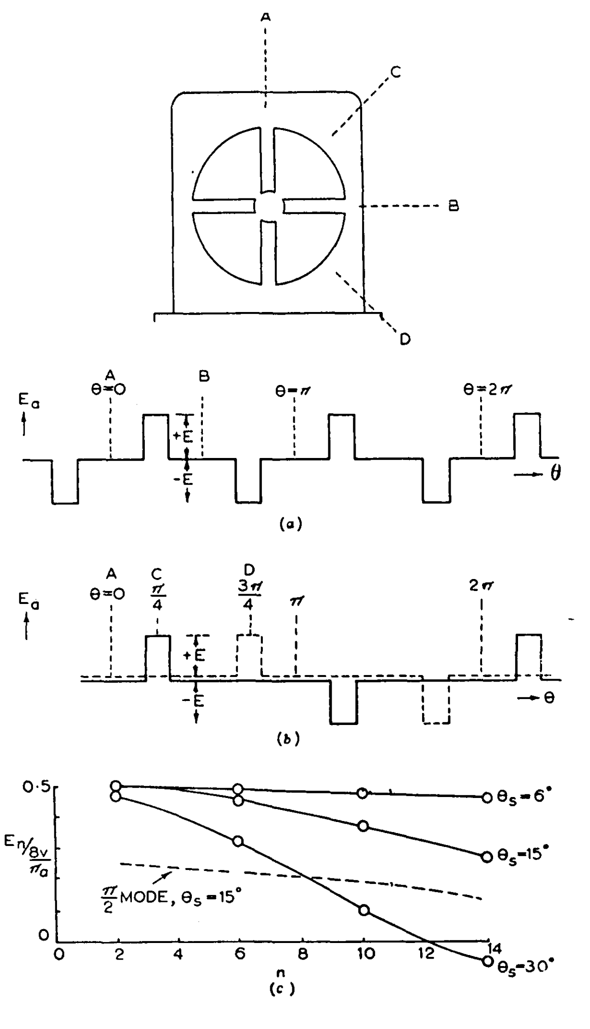


Fig. 5.—Field distribution and component amplitudes for π and $\pi/2$ modes (s.a.).

(a) Field distribution; π mode.
(b) Field distribution; $\pi/2$ modes; C and D symmetry.
(c) Component amplitudes.

(4) ANALYSIS OF MECHANISM OF OSCILLATION OF S.A. VALVE

(4.1) Modes of Resonance

As in the m.s. case with four gaps, four modes of oscillation of the anode system are possible, the π mode, the two $\pi/2$ modes and the zero mode. In the $\pi/2$ mode, owing to the symmetry of the system, the two components now have the same field distribution, but these are displaced in space by 90°, having the alternative distributions shown in Fig. 5(b), with axes of symmetry C and D. It will be noted that for each of these modes there is no field in two alternate cavities.

With two gaps, only two modes of resonance can be excited as before, the π mode and the zero mode, the latter occurring at a relatively high frequency.

(4.2) Analysis of Interaction Field

(4.2.1) Oscillation in the π Mode (Four Segments).

For the π mode [Fig. 5(a)] the amplitudes of the components of the field present at the anode surface may be written, following the previous Section, as

$$E_n = \frac{8V}{\pi a}\left[\frac{\sin \frac{1}{2}n(\theta_2 - \theta_1) \sin \frac{1}{2}n(\theta_2 + \theta_1)}{n\theta_s}\right]$$

with the restriction that only even values of n are permissible. Further, the condition $\theta_2 + \theta_1 = \pi/2$ means that all values of n which are divisible by four have zero amplitude.

With these restrictions the amplitude of all components may then be written as

$$E_n = \frac{8V}{\pi a}\left(\frac{\sin \frac{1}{2}n\theta_s}{n\theta_s}\right)$$

It is clear that by adjustment of the value of $\theta_s = \theta_2 - \theta_1$ other components may be made zero, if the possibility of interaction with them needs to be avoided. For example, if $n\theta_s$ is made 216° for $n = 6$ it will equal 360° for $n = 10$, i.e. the amplitude is zero for $n = 10$, so that this component is not excited.

Fig. 5(c) shows the relative amplitudes of the different components for $\theta_s = 6°$, 15° and 30°. It will be noted that for the same gap widths (6° and 15°) the amplitudes of the components $n = K$ are the same as for the m.s. case in Fig. 3(b). However, for $n < K$ the amplitudes are much greater. On the other hand, fewer components are present.

(4.2.2) Oscillation in the $\pi/2$ Mode (Four Segments).

For both $\pi/2$ modes, the amplitude of components is

$$E_n = \frac{4V}{\pi a}\left(\frac{\sin \frac{1}{2}n\theta_s}{n\theta_s}\right)$$

with only odd values of n permissible. Thus the envelope of the amplitude of both $\pi/2$ modes is the same as that for the π mode, with only odd values of n present, but with the envelope amplitude reduced to one-half, as indicated in Fig. 5(c).

(4.2.3) **Oscillation in the π Mode (Two Segments).**

The amplitude of the separate components is given by

$$E_n = \frac{4V}{\pi a}\left(\frac{\sin \frac{1}{2}n\theta}{n\theta_s}\right)$$

with the restriction that only odd values of n are possible. The envelope is accordingly the same as that for each component of the $\pi/2$ mode for four segments.

(5) CIRCUIT DESIGN AND LOAD COUPLING

The 2-segment structures are of particular interest for tuning by an external circuit. In order to obtain maximum tuning range the cavities of the 2-segment s.a. structure were shaped to the form of Fig. 6(*a*).

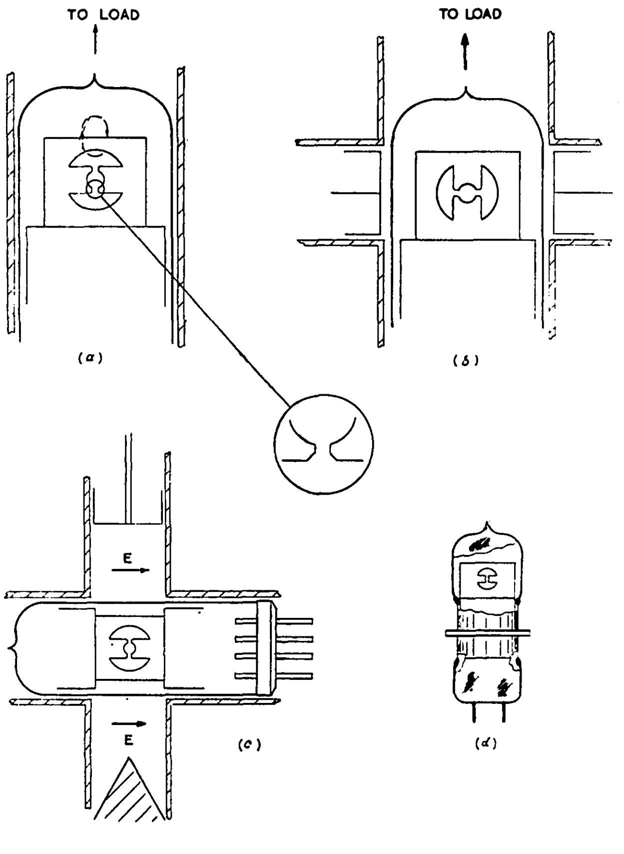


Fig. 6.—Arrangements of 2-segment symmetrical anode.
(*a*) Single magnetic coupling.
(*b*) Double magnetic coupling.
(*c*) For very heavy loading.
(*d*) For higher dissipation.

It was also found possible to dispense with the coupling probe of the two types first used, and to couple magnetically from the current circulating round one of the cavities as shown in the Figure. The alternative arrangement at Fig. 6(*b*) allowed coupling from two resonators to be achieved by rotating the anode through 90°.

(6) PROBLEMS OF VALVE CONSTRUCTION

It will be clear that the achievement of satisfactory performance in valves of the type proposed is greatly dependent on satisfactory mechanical design, and a considerable amount of effort was devoted to problems of valve construction.

(6.1) Cathode Structure Assembly

Experience on other magnetrons had indicated that if a reasonable efficiency and noise performance was to be achieved it would be necessary to use the largest possible ratio between starting current and operating current. With the limited anode dissipation it was therefore essential that the stray current be kept extremely small. That this would depend largely on accurate cathode centring was well known, but whether the necessary accuracy could be achieved without involving high manufacturing skill was uncertain. A number of methods of mounting the cathode were tried with gradually improved results, and in a final arrangement satisfactory performance was obtained. In this the mica mounting pins were moved down to a point near the zero-potential plane for the anode to reduce trouble from possible resonances. They were inserted in the anode block and fixed by deforming the copper around them with a circular tool. Then two metal eyelets were placed on the pins on one side of the anode block. The mica, which now had two clearance holes for the eyelets and a clearance hole for the cathode, was placed in position with a cathode end-shield located by four metal tags loosely mounted on it. This shield, which was made from sheet nickel treated with titanium dioxide, carried the central cathode hole. A jig, fitted with a spigot of the cathode diameter, was then inserted in the anode bore. The eyelets were deformed to clamp to the mica, and the four tags on the end-shield were compressed to fix tightly to the mica. This process was repeated for the second mica, and finally the central jig was removed and the cathode inserted.

A high standard of consistency of cut-off characteristics was achieved by this method, and it was then possible to measure the variation of starting current with anode form (arising from different methods of construction) without cathode eccentricity masking the effects investigated. Fig. 7 shows the cut-off characteristics obtained with different methods of cathode mounting, the "very good" characteristic being obtained with the method described.

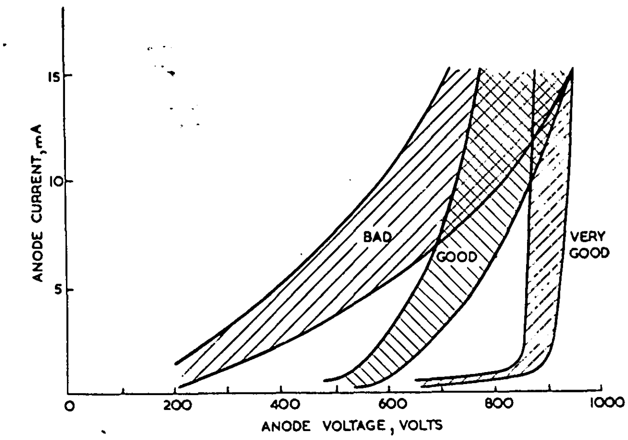


Fig. 7.—Cut-off characteristics for $H = 2\,400$ oersteds.

(6.2) Anode Construction

The early anodes of the m.s. type were made by straightforward machining methods, but difficulties were experienced in obtaining the long slots required with sufficient accuracy of form and position. It was found worth while so far as circuit losses were concerned to increase the diameter of the output probe from 0·014 to 0·024 in, the largest wire which could be accommodated in the narrow tongue between the circuit slots.

The first anodes of the s.a. type were made by fabrication, and the opportunity was taken to form the output coupling probe as part of one of the vanes of which the anode was made, as can be seen in Fig. 1. Later designs used magnetic coupling. Finally, hobbing was used, and this considerably simplified the manufacture, since the anode block could be a straightforward section from a hobbed billet. The need for two machined steps on both sides of the block was also eliminated, and the eyelets holding the mica to the pins were so constructed that the mica was supported away from the block to ensure a high electrical leakage path between anode and cathode.

The anode bore of both 4- and 2-segment blocks was drilled after the anodes were hobbed in early valves, but later it was found possible to construct a hob for forming the anode circuits and central hole together. In the 4-segment case the hob of 80/20 nickel-chromium base alloy was fabricated from two parts; the outer part forming the anode circuits and vanes had a pin of 2 mm diameter inserted centrally to form the anode bore. In the 2-segment anode, owing to the comparatively thin vane forming the segment gaps, it was not possible to use a 2-part fabrication method, and in this case the hob was made by form-grinding a hot-process die steel, care being taken to obtain the minimum radius at the junction of the anode bore and segment tips.

Valves of this type and size (all of 2 mm anode bore and 2·5 mm anode length) are capable of handling an anode dissipation of 8 watts; the temperature of the glass envelope sets the limit to the output of the valve. One method of increasing this dissipation is to provide a high-conductivity connection between the anode and an external cooling element, and this has been tried in a valve having the arrangement indicated in Fig. 6(*d*). Such a design is likely to increase the cost of the valve somewhat, but the essential simplicity of the electrical design is not affected. The anode dissipation is increased to at least 30 watts, and there is a consequent increase in power output.

(6.3) Cathode

The cathode used in all the experiments described consists of nickel tube of 0·625 mm outside diameter, 0·525 mm internal diameter, spray coated to 0·025 mm thickness over 2 mm length with a mixture of ammonia-precipitated barium and strontium carbonates. The heater supply for 800° C, with the cathode located rigidly to the mica by means of the cathode end-shields, is at 0·3 amp and 6·3 volts. Difficulties due to delamination of the mica around the cathode end-shields were overcome by increasing their thermal emissivity with a coating of titanium dioxide furnaced in dry hydrogen to a fine black deposit. The cathode back-bombardment power is normally 3–5 % of the anode power; consequently at 8 watts input to the anode a reduction of heater power is necessary. The filament is 0·045 mm molybdenum wire spray-coated with alumina 0·052 mm thick. The eyelets, pins, assembly support pressing and fixings are all of non-magnetic material. A barium getter is mounted near the base and, prior to sealing into the bulb, the base is coated with magnesium oxide. In spite of the close proximity of the getter to the base pins no breakdown occurs at 2 000 volts.

(6.4) Processing

The valves are baked on the pump at 380° C for ten minutes to outgas the glass. The complete assembly is then outgassed by eddy-current heating at approximately 750° C. The cathode is flashed at 10 volts to break down the carbonates, after which the getter is flashed and the valve sealed off from the pump.

(7) OPERATION OF 4-SEGMENT M.S. VALVES

Fig. 8 shows a preliminary operating characteristic obtained with a good valve of this type delivering power to a matched load,

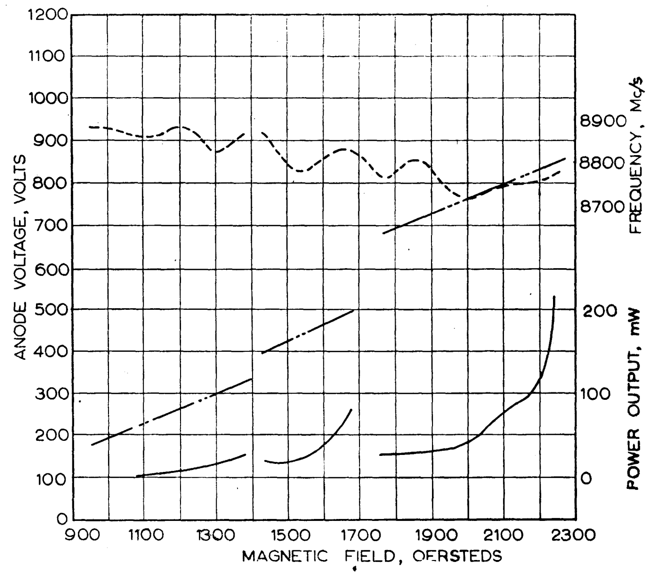


Fig. 8.—Performance of 4-segment m.s. valve.

- - - - - Frequency.
—·—·— Voltage.
———— Power.

the coupling being adjusted at each reading to give maximum power output. Power is obtained over a number of discrete ranges of magnetic field corresponding to different component numbers, and there is little variation of frequency as it is essentially that of a single mode of the circuit oscillations. Small changes with operating conditions are due to changes in the admittance of the electron stream.

On correlating the observed ranges of operating voltage with those derived from calculation of threshold voltage[2] over the range of magnetic field for which a given mode is excited, it appears that operation at high magnetic fields is in the component $n = 5$, and at lower fields in the components $n = 6$, 7 and possibly 8. This is at variance with the analysis already given for this type of structure (Section 3.2.1) from which it is to be expected that either odd or even components only would be excited for a given circuit mode. The appearance of both families may be due to some asymmetry of the structure arising, for example, from inaccurate spacing of the circuit gaps.

(8) OPERATION OF 2-SEGMENT M.S. VALVES

Fig. 9 shows a performance chart for one of these valves when feeding into an output circuit of the type shown in Fig. 15(*a*). Useful output was obtained but over more limited ranges of operating conditions than for the 4-segment valve. For these tests, coupling of the valve to the load was adjusted for every reading. Comparison of calculated and observed operating voltage showed that the two components observed were $n = 5$ and $n = 6$. No oscillations were observed at lower magnetic field and voltage for modes other than those indicated, and it was concluded that this is simply because the r.f. field in the interaction space is too low for higher-order modes to be excited. As oscillations in both components cease, owing to increase of current to the limit of oscillations, the voltage rises sharply to a value which is rather below that calculated for the critical voltage.

(9) OPERATION OF 4-SEGMENT S.A. VALVES

All valves for which data are given here used magnetic coupling, and Fig. 10 shows a contour diagram of a 4-segment valve coupled to a load through a matching transformer in the way indicated in Fig. 15(*a*). It will be seen that there are three

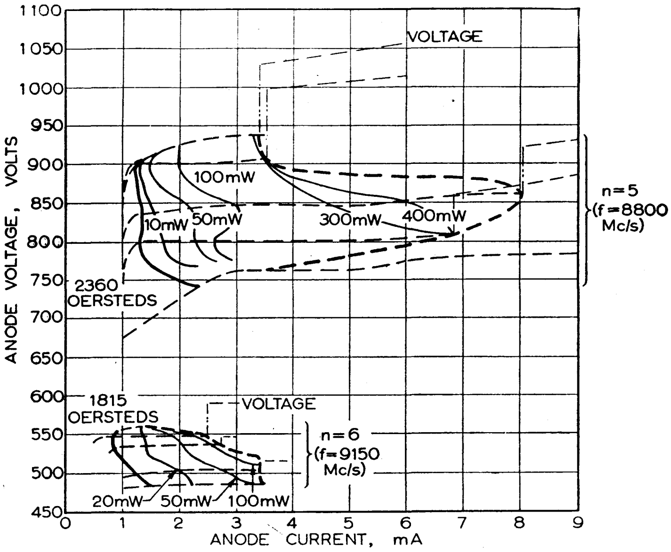


Fig. 9.—Performance of 2-segment m.s. valve.

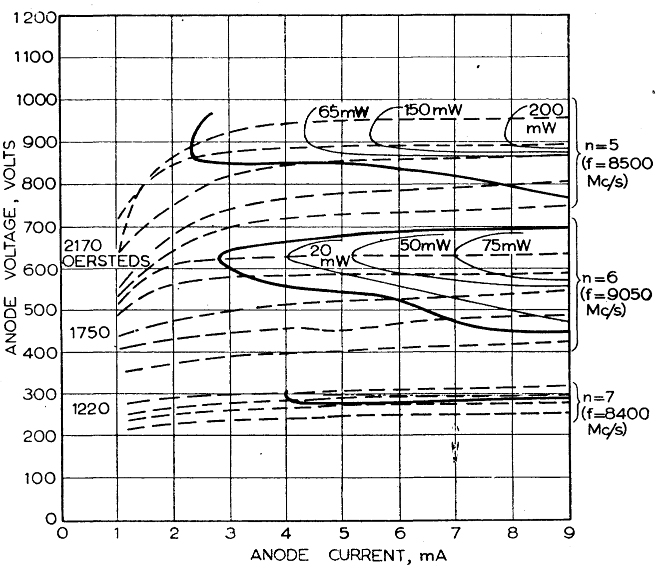


Fig. 10.—Performance of 4-segment s.a. valve.

regions of oscillation, two being of approximately the same frequency. Comparison of observed and calculated operating voltages suggest that these operate through the components $n = 5$, 6 and 7. The earlier analysis indicates that oscillation of the 4-segment anode in the π mode results in the space components $n = 2$, 6, 10, etc., whilst oscillation in the $\pi/2$ mode results in the space components $n = 1$, 3, 5, 7, 9, etc. Accordingly, it is concluded that the higher-frequency oscillation with $n = 6$ is due to excitation of the resonators in the π mode, the other oscillations of both higher and lower voltage being due to excitation in the $\frac{1}{2}\pi$ mode.

It will be noted that the π mode is excited only by one component, others being widely spaced in number.

A c.w. power of 75 mW is generated at a voltage of 600 volts with a current of 9 mA.

Tests have been made to high currents with narrow pulses of low duty cycle. At a magnetic field of 2000 oersteds and voltage of 650 volts a peak power of the order of 1 watt has been obtained with a peak current of 100 mA, with pulses of 2 microsec duration repeated 2000 times a second.

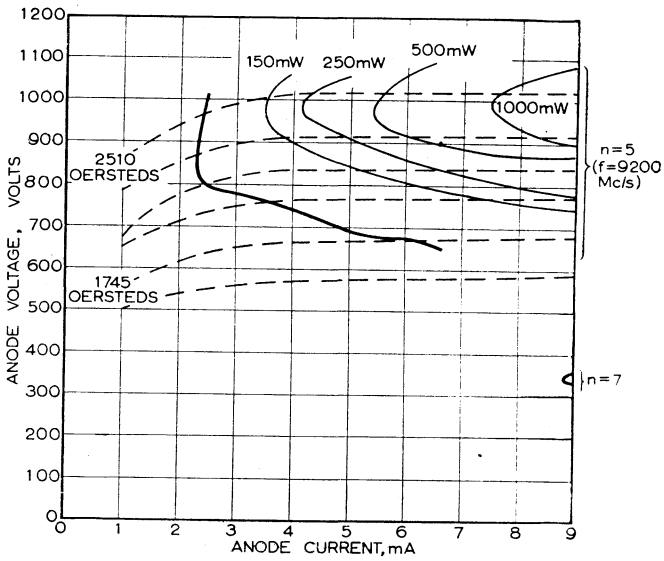


Fig. 11.—Performance of 2-segment s.a. valve.

(10) OPERATION OF 2-SEGMENT S.A. VALVE

Fig. 11 shows a contour diagram under matched load conditions measured in the circuit shown in Fig. 15(*a*) with operation obtained in the component $n = 5$ only at the normal values of current.

A power of 1 watt is obtained with a magnetic field of about 2450 oersteds, a voltage of 970 volts and a current of 7·5 mA, the efficiency being about 14%. Short-pulse operation to higher powers is also possible.

By increase of current, carried out most conveniently with low-duty-cycle operation, the $n = 7$ component could be detected at low magnetic field, and Fig. 12 shows the frequency/magnetic-

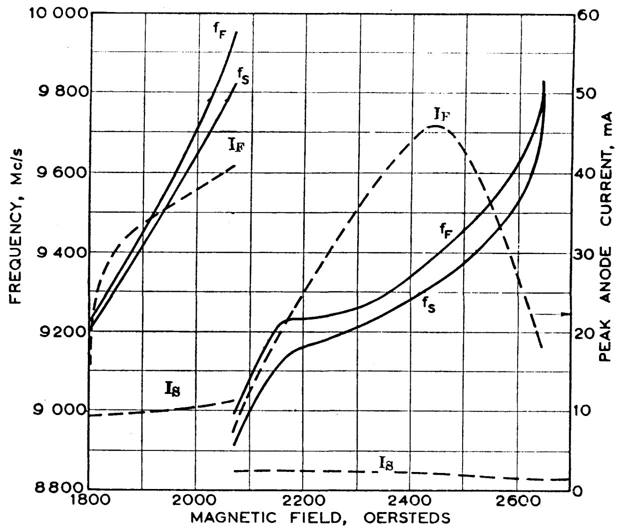


Fig. 12.—Variation of frequency and limiting currents with magnetic field.

field characteristic for both components at currents for the start and finish of oscillations. The variation in frequency over the current range is small compared with that over the magnetic-field range. At fixed current a frequency variation of at least 400 Mc/s may be obtained by variation of magnetic field. It is rather higher than the figure obtained with the 4-segment design.

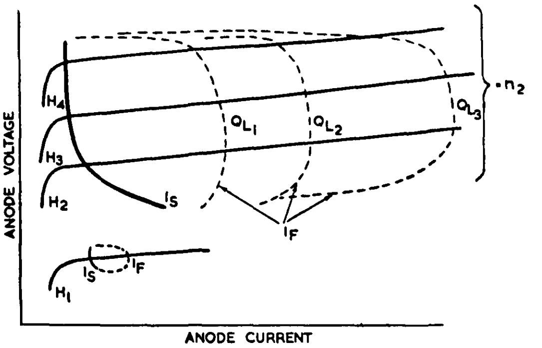
Valves of this type, for which the above characteristics were obtained, were constructed with plain anode gaps of width 0·018 in. Earlier valves had gaps of 0·020 in, and these gave consistently lower efficiency (of the order of 3% instead of 14%). Valves made later with the gap still at 0·018 in but the capacitance reduced by chamfering as in Fig. 6(*a*) have shown higher efficiencies still, and these have been in the neighbourhood of 25% for the component $n = 5$. This change improves the strength of the hob used for anode construction.

Experience in this work of changing gap dimensions and proportions has shown that, as would be expected, it is very necessary to maintain sharp corners at the junction between the anode surface and the interaction gap, otherwise the starting current may be significantly increased and the efficiency consequently decreased.

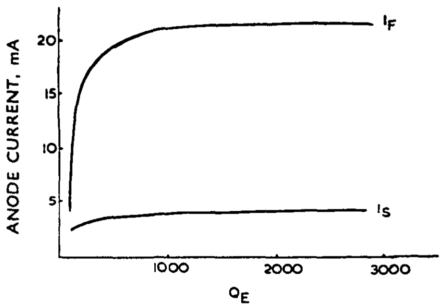
The change of efficiency resulting from these effects is, however, greater than would be expected from the change in the amplitudes of the r.f. field components.

(11) EFFECT OF LOAD COUPLING ON STARTING AND FINISHING CURRENTS

The influence of circuit loading on the starting and finishing currents (I_S and I_F) is shown generally in Fig. 13(*a*) for the valves



(*a*)



(*b*)

Fig. 13.—Influence of load coupling on I_S and I_F.

(*a*) Contour diagram.
(*b*) Variation of I_S and I_F with Q_L.

whose characteristics have been described. These valves have a ratio r_c/r_a of cathode to anode diameter of 0·31, and it is possible that variation of this ratio will modify these characteristics.

In the higher field range (H_2, H_3, H_4) where operation is in the component n_2, the starting current falls somewhat with increasing magnetic field at a given overall circuit Q-factor of Q_L. It is little affected by circuit loading, and this behaviour is consistent with the presence of significant (though small) stray currents whose magnitude is not greatly dependent on the presence of normal oscillations.

On the other hand, the current at which oscillations cease, I_F, varies significantly and is strongly dependent on Q_L. It appears that I_F is determined entirely by the magnitude of the r.f. field coupling to the electron wave. At low magnetic field this is small, because of low efficiency, and it increases markedly as efficiency is increased with magnetic field. At high magnetic field, however, owing to shrinkage of the electron cloud the r.f. coupling field falls again, even though the r.f. field may be large at the surface of the anode.

This behaviour is repeated for the higher-order component n_1 at the lower magnetic field H_1, although over a much smaller range of parameters.

Fig. 13(*b*) shows values of both currents I_S and I_F at a fixed magnetic field plotted as a function of Q_E, this being the component of Q_L which is due to the external load only. These data were taken on a 2-segment s.a. valve having a "side" coupling to tuning waveguides (see Section 14). It will be noted that I_F increases markedly with Q_E but reaches a limiting maximum when Q_E becomes so large that it has little effect on the overall loss factor Q_L.

(12) FREQUENCY CHANGE WITH CURRENT

It has been found that the change of frequency with current (frequency pushing) is much greater with spatial-harmonic operation than with fundamental operation. Measurements were made of the frequency change with current of a 2-segment s.a. valve operating at a magnetic field of 2300 oersteds in the $n = 5$ component when modulated over the current range of 1–9·5 mA. The valve was coupled to the output waveguide sufficiently tightly to give maximum power output. It was found that the rate of change of frequency with current varied little over the range and was of the order of 14·5 Mc/s/mA. The output waveguide was then mismatched by a probe giving a standing-wave ratio of up to 1·75, and the rate of change of frequency with current was measured as the mismatching probe was moved along through a guide length of greater than a half wavelength for different values of the mismatch. It was, however, necessary to limit the current to 6·5 mA for the mismatch setting giving the highest load conductance at the valve.

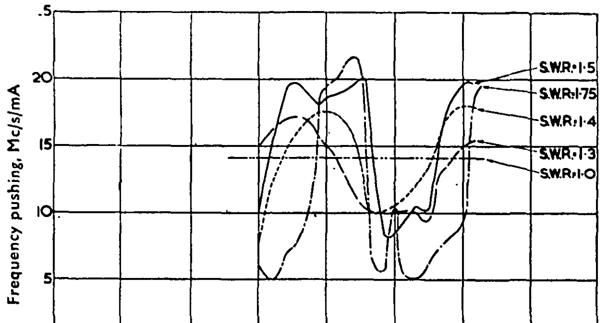


Fig. 14.—Variation of frequency pushing with circuit loading.

Fig. 14 shows the values obtained over the range of loading parameters, the high figures corresponding to maximum load conductance and the low figures to low conductance. A peak value of 21·5 Mc/s/mA is obtained with a peak frequency excursion of the order of 170 Mc/s (at slightly less than maximum conductance). For a power variation of not more than 3 dB from the peak value a frequency excursion of rather less than half the above value is obtained.

(13) FREQUENCY CHANGE WITH CURRENT UNDER CONDITIONS OF EXTREME CIRCUIT LOADING

One possibility offered by the simple resonant system used in this work is that of investigation of magnetron performance in the condition where coupling of the load to the resonant circuits is so tight that the impedance measured at the interaction gaps loses its resonant properties and becomes resistive. Under this condition general considerations suggest, and work elsewhere has confirmed, that it is possible to vary the frequency generated over a wide range by alteration of the velocity of the electron cloud circling the cathode, by variation of applied voltage, magnetic field, or both. Measurements by Wilbur and Peters[3] at frequencies of the order of 550 Mc/s showed that variation of frequency over a range of the order of 2:1 could be obtained with power output of upwards of 20 watts. In order to obtain a signal with a line spectrum, reduction of emission to either partial or full temperature limitation was required.

Similar performance was obtained by Guénard and Huber,[4] but in their case no requirement was found for emission limitation.

Only preliminary measurements have been made on valves of the 2-segment s.a. type with the structure modified as indicated in Fig. 6(*c*) to increase the coupling to the load by adding an additional choke. With this arrangement the normal oscillations of substantially fixed frequency could not be obtained, but on operating the valve with a varying anode voltage at 50 c/s it was observed that output was obtained over a range of frequency.

Preliminary measurements were made on a number of valves of this type and in all cases a frequency change of at least 1 000 Mc/s was obtained with variation of anode current, the mean frequency being of the order of 9 500 Mc/s. By altering the arrangement for coupling the valve to the load circuit so that the low-frequency cut-off arising from the output waveguide was eliminated, it was found possible to detect output energy over the range 10 000–5 000 Mc/s by exploring over an extreme range of current. The power measured in this case was significantly less than that with normal operation; about one milliwatt was obtained with a peak current of 40 mA.

In these experiments no sign was seen of the requirement for a particular emission condition. A clean spectrum was obtained with normal space-charge limitation of emission, and this is of particular importance for the practical utilization of this type of operation. On the other hand, the absence of temperature limitation results in large variation in anode current and power over a useful frequency range.

(14) MECHANICAL TUNING

One of the advantages envisaged from the start of this work, for the structure described in this paper, was the possibility of wide-range mechanical tuning by means of an externally coupled reactance. The single mode of operation of the 2-segment valve, in particular, should allow considerable tuning ranges to be achieved.

A number of different tuning circuits and arrangements have been tried and are indicated schematically in Fig. 15.

An arrangement used for investigation of the tuning performance of the 2-segment m.s. design is shown in Fig. 15(*b*). No deliberate damping of the tuning circuit by a load was employed, and the valve projects into the resonant circuit formed by a piece of rectangular waveguide which is terminated by a tuning piston. A wavemeter coupled loosely to the cathode leads of the valve showed that a tuning range of over 1 000 Mc/s could be obtained in the higher-voltage mode. In this case, although no power was delivered to a useful load, the power transmitted through the wavemeter from the heater leads was of the order of 1 mW, so that in fact a power of at least 10 mW was probably being radiated.

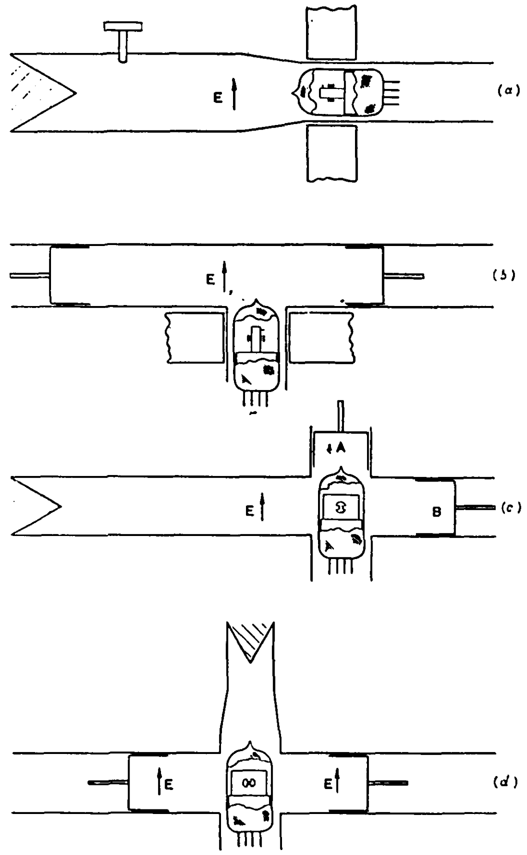


Fig. 15.—Coupling and tuning circuits.

The arrangement which has been found most convenient in use with 2-segment s.a. valves having end coupling is that shown in Fig. 15(*c*). In this the valve is coupled by its magnetic field to the tuning waveguide, A, the coupling being adjusted by the degree of insertion of the valve into the circuit and by the position of piston B. The load circuit is coupled by series connection to the output waveguide.

Fig. 16 shows characteristics of frequency and power measured as a function of position of the tuning piston with piston B set to give either maximum power output at some part of the range or minimum power variation over the range. In the first case a tuning range of $7\frac{1}{2}\%$ of the mean frequency is obtained with a minimum power of 170 mW and maximum power of 660 mW. With the piston set to give minimum power variation, a tuning range of $4 \cdot 3\%$ is obtained with a minimum power of 200 mW and a maximum of 235 mW. These figures apply to operation with constant magnetic field. It will be expected from the characteristics shown in Fig. 12 that some further increase of tuning range of the order 200–300 Mc/s may be achieved by variation of magnetic field.

The arrangement used in the loading experiments described in Section 12 is shown in Fig. 15(*d*). Here a 2-segment valve with double coupling, as shown in Fig. 6(*b*), is used. By movement of the tuning plungers symmetrically relative to axes of the valve, tuning may be obtained with zero coupling to the load. By displacing one tuning piston by a given amount from its setting for a particular frequency, and the other piston by a similar but negative amount, the frequency may be left substantially unchanged, although the coupling to the load may be increased to a desired value. Thus, independent control of frequency and load coupling is achieved, and a wide range of loading may be covered.

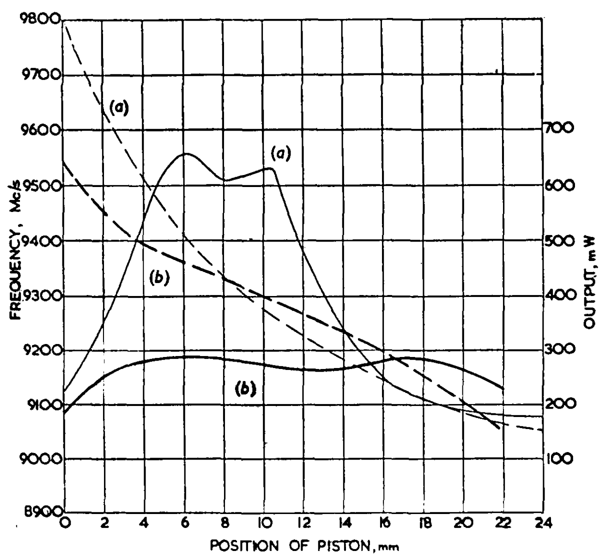


Fig. 16.—Tuning characteristics of 2-segment s.a. valve.

(*a*) Adjusted for maximum power output.
(*b*) Adjusted for minimum power variation.

——— Power.
- - - - - Frequency.

Experience obtained in mechanical tuning of valves of this type is so far only preliminary, and it is considered that wider tuning ranges may be eventually obtained with sufficient attention to the design of tuning circuits. More rapid control of frequency may be obtained by the use of a phase shifter of the ferrite type, with which the change of electrical length of the tuning waveguide may be effected by change of the magnitude of polarizing magnetic field.

(15) NOISE PERFORMANCE

Few data have so far been obtained on the noise performance, but preliminary measurements of amplitude-modulation noise indicate that the level is low enough for the valve to be used as a local oscillator in a superheterodyne receiver with a bandwidth of a few megacycles per second without degradation of receiver sensitivity due to local-oscillator noise.

(16) OSCILLATION BUILD-UP TIME

One parameter which is of interest in low-power microwave generators is that of time of oscillation build-up. In some applications it is desirable for this to be as short as possible. The use of an anode structure of the type here described appears to allow the possibility of very short build-up time with minimum time jitter, since interfering effects due to the generation of unwanted modes are minimized and, in fact, are not present in the 2-segment structure. No detailed measurements have been carried out, but preliminary indications are that very rapid and stable starting is achieved when pulses considerably less than 0·1 microsec long are generated, the limit of build-up time being so far set by the shape of the current pulse which can be generated.

(17) LIFE

The most probable cause of failure in valves of this type is loss of cathode emission. With the limit of anode dissipation imposed by the structure (see Section 8) the maximum emission required is 0·2 amp/cm at a frequency around 10 000 Mc/s. In practice a value somewhat lower than this will normally be used. Providing, therefore, that the cathode temperature does not exceed 1 000° K, thorough outgassing and adequate gettering should ensure a long life.

(18) CONCLUSION

It appears that the use of spatial-harmonic operation can lead to designs of magnetron having attractive characteristics of performance, design and construction.

Work is still being carried out, but the results reported here, although preliminary in nature, are sufficient to indicate the potentialities of this type of operation.

(19) ACKNOWLEDGMENTS

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