LOW-POWER RESONANT-SEGMENT MAGNETRONS FOR CENTIMETRE WAVES*

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SUMMARY

This paper describes the development and use of a range of small glass magnetrons for use as low-power sources in the centimetre band. Although originally designed for measurement purposes and as local oscillators in receivers, they have proved most useful as oscillators for centimetre-wave transmitters. These magnetrons have an anode system consisting of a number of interleaved segments and are provided with an indirectly-heated oxide-cathode; they are generally similar in form to a small glass receiving valve. They oscillate at a wavelength which is largely decided by the length of the anode segments, but can be tuned over a narrow range by variation of the applied magnetic field or by adjustment of the external circuit.

A series of experimental valves has been made covering a wavelength range of 4·5 to 11 cm with outputs of the order of 0·1 watt at 4·5 cm increasing to 0·5 watt at 11 cm. Three types taken from this experimental range were modified for production in larger quantities, namely the E1210 for 9·1 cm and the CV79 and CV89 for two wavelengths in the region of 6·5 cm. Some characteristics of these established designs are presented together with descriptions of their associated circuits. Methods of modulation are referred to, particularly the application of pulse-width modulation. With a transmitter using this system of modulation applied to an E1210, radio telephony at centimetre waves is possible with quality comparable with that obtainable at longer wavelengths.

(1) INTRODUCTION

The earliest models of the valves described in this paper were developed in the summer of 1940, when centimetric radar was beginning to take practical shape. They were intended as sources for laboratory measurements and to explore their possibilities, in competition with positive- and negative-grid triodes and velocity-modulation valves, as local oscillators for superheterodyne receivers. About a year later they were first used as low-power transmitters. With the large aerial gains which can conveniently be realized on centimetre waves the small powers they produce have proved adequate for communication up to distances of the order of 50 miles, usually though not exclusively within the optical horizon.

The valves are essentially multi-segment, glass-envelope magnetrons with indirectly-heated oxide cathodes. The anode segments themselves form the multiple oscillatory circuit, and the valve is normally mounted in a wave guide to which the output power is radiated from the resonant anode system through the glass bulb. A small amount of tuning is possible either by varying the magnetic field-strength or by "pulling" by means of a suitably-coupled circuit.

In the original experimental series the main objective was to produce powers of the order of a fraction of a watt, at wavelengths of about 10 cm and below, with conveniently low anode voltages (of the order of 250–750 V) and small magnetic fields (of the order of 500 oersteds) without, at the same time, requiring particularly small electrode clearances. The resulting design is, in fact, very much like an ordinary receiving valve in appearance and in constructional technique. The requirements as regards electrode symmetry are, however, more stringent; and, particularly for communication applications, individual testing of a much more searching character is normally required The latter is, however, an inevitable result of combining valve and oscillatory system in one unit and is a common characteristic of many centimetre-wave devices.

By comparison with the high-power magnetron designs developed for radar transmitters the applications of the valves described here have been relatively limited, and the research effort available for their study correspondingly restricted. They have, however, performed very usefully in their limited field; the 9-cm form, in particular, has achieved a high standard of reliability and life. Apart from modifications mainly of a mechanical character these designs are essentially those of about 5 years ago, and different techniques may well be adopted for similar applications in the future. But in addition to performing their war-time functions these valves have provided operating data which will be very valuable in the future development of centimetre-wave communication systems.

(2) GENERAL CHARACTERISTICS

(2.1) Constructional

The construction of the resonant-segment system, of the type originated by Gutton and Berline,§ is illustrated by the drawing in Fig. 1, which shows the electrode system used in the earlier 9-cm valves. The anode segments are attached alternately to two end rings which are connected by a stirrup; in this case the stirrup forms a closed line about a quarter-wavelength long so

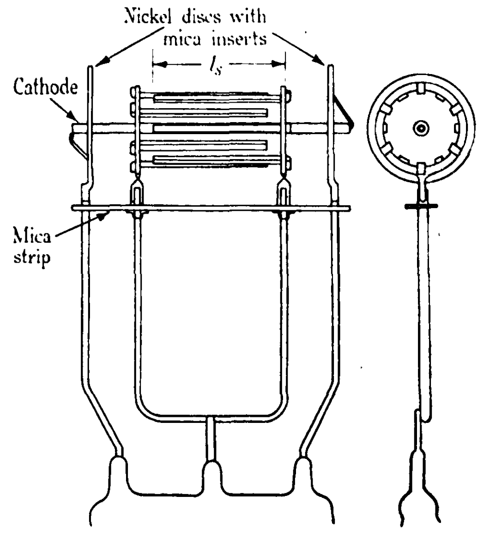

Fig. 1.—E1210 construction.

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‡ Admiralty Signal Establishment; formerly member of G.E.C.-M.O.V. Research Group, Wembley, England.

§ Gutton, H., and Berline, S.: *Bulletin de la Société Française Radioélectriciens*, 1938, 12, pp. 30 and 120.
See also Megaw, E. C. S., "The High-power Pulsed Magnetron: a Review of Early Developments," *Journal I.E.E.*, 1946, Pt. IIIA, p. 977.

that the anode system is unaffected by its support. The oxide cathode, of conventional receiving type, is mounted between two nickel end-shields which prevent electron bombardment of the bulb walls; it is supported from them by mica discs of which only a very small part is exposed on the inside. Insulation is necessary only at one end, but both ends were made the same for mechanical convenience. Heater and cathode are electrically connected to one end shield and the free end of the heater to the other. A mica bridge connects anode and cathode systems for mechanical rigidity, and the whole system is carried on a simple 3-wire foot-tube.

As a first approximation the anode segments may be regarded electrically as quarter-wave resonators "earthed" at the rings, though in fact with the arrangement shown there may be an appreciable r.f. potential difference between the rings, and there is also localized capacitance between the free segment ends and the opposite ring. As is shown later the segment length, in Fig. 1, is the main factor which determines the oscillation wavelength, but this wavelength is of the order of 10 times rather than 4 times the segment length. The simplest mode of oscillation (in which the valves were intended to operate) is that in which all the segments on one side oscillate in phase and those on the other side in the opposite phase, i.e. 180° phase difference between adjacent segments as in ordinary 2- and 4-segment magnetrons with external oscillatory circuits. Other modes of oscillation are, however, possible—with slightly different wavelengths and with smaller inter-segment phase differences. In general there are as many modes as there are pairs of segments and there is obviously also a much lower frequency mode (in the decimetre region) in which the anode supporting stirrup acts as an inductance tuned by the total inter-segment capacitance, but this is excited only with magnetic field values much below those normally used.

In some of the early valves the output was coupled to the load by means of a two-wire line, of about 250 ohms characteristic impedance, which was sealed through the end of the bulb. This line was tapped on to two adjacent segments near their "earthed" ends. By this means it was hoped to obtain a relatively large tuning range but in fact only about 5% was obtained; experiment showed that neither efficiency nor tuning range was critically dependent on the tapping points on the segments. The variation of frequency with circuit tuning was appreciable only when the length of this line was near an integral number of half-wavelengths. As the reactance between the end rings is probably of the same order as the characteristic impedance of the line, or lower, this is to be expected.

This line-coupling system was soon abandoned in favour of using the resonant anode system directly to excite an H_{01} wave in a rectangular guide in which the valve was mounted. This enabled the valve to be a simple single-ended one and avoided the awkward screening problems of open lines at very high frequencies.[*] Rather contrary to expectation there was only a slight improvement in overall efficiency with the guide as compared with the line arrangement, provided proper precautions were taken to minimize radiation loss in the latter; but the gain in convenience was great.

(2.2) Operation

The mechanism of operation of multi-segment magnetrons has been discussed in recent papers elsewhere.[†] Here it need only be recalled that the operating anode voltage depends on the valve dimensions, the magnetic field-strength, the wavelength, and the mode of oscillation characterized by the number, n, of repeats in the voltage standing wave round the anode. (For the simplest oscillation mode, mentioned above, n is equal to half the number of segments). This voltage is ordinarily close to the "threshold" value given by

$$V_T = 943\,\frac{a^2}{n\lambda}\left[H\left(1-\frac{b^2}{a^2}\right)-\frac{10\,700}{n\lambda}\right] \text{ (practical c.g.s. units)}$$

where a = anode radius.
b = cathode radius.
H = magnetic field strength.
λ = wavelength.

The efficiency, apart from circuit losses, depends on the value of $n\lambda H(1-b^2/a^2)$ and tends to zero when this factor falls to $21\cdot 4\times 10^3$.

These valves were required for low-power applications in which relatively low efficiency is acceptable, but in which it was desired to keep the anode voltage and magnetic field as low as possible without using electrode clearances so small as to require highly specialized techniques in manufacture. Hence the anode radius a was made a few millimetres and a number of segments was used which would allow oscillation to be generated at magnetic fields obtainable from simple permanent magnets weighing only a few pounds. The expression given above shows that increasing the ratio of cathode to anode radius appreciably increases the magnetic field for a given efficiency if it is of the order of a half or more. In this case where c.w. operation, or operation involving peak anode currents not very large compared with the mean, was required, no difficulty was anticipated in obtaining adequate cathode emission. A relatively small cathode size, about 0·2 ratio of radii, was therefore adopted.

The question of cathode-emission requirements was not examined very carefully in the early experiments because, as expected, no practical difficulty was encountered. Examination of the results of emission tests carried out later show that it is not the "total" thermionic emission which is the significant value, as previously assumed, but rather the maximum space-charge-limited emission, i.e. the value of current at which the diode current/voltage characteristic begins to depart from the three-halves power law owing to the onset of temperature limitation. Approximately at least, this latter value should equal or exceed the maximum anode current at which the valve is required to operate. This result applies to magnetrons operating with anode voltages of the order of 500 V or less. This may seem surprising by comparison with the fact, that at anode voltages of the order of 1 kV or more secondary emission produced by accelerated electrons returning to the cathode can reduce the thermionic emission required to a small fraction of the operating anode current. The explanation almost certainly lies in the fact that at anode voltages below about 1 kV the velocity of the bombarding electrons is so low that the secondary-emission coefficient of the oxide cathode is too small to produce a significant contribution to the total emission.

In designing the original electrode systems it was assumed that the oscillation mode would be that giving 180° inter-segment phase difference. From the operating data given later it is not certain that this is actually the case; when the magnetic field-strength is not much above the minimum value for oscillation it is difficult to distinguish with certainty between adjacent, and fairly large, possible values of n from the operating data. It has not been possible to carry out direct measurements of the voltage distribution on the segments, though such measurements would be of considerable interest.

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[*] The authors have recently learned from Dr. Gutton that the same conclusion was reached by the French workers.

[†] See MEGAW (*loc. cit.*) and the companion paper by WILLSHAW and others. At the time these valves were designed the detailed analysis of magnetron operation now available had not been carried out. Design formulae based on more elementary conceptions, but leading to similar conclusions for the designs considered here, were in fact used.

(3) INITIAL EXPERIMENTAL DESIGNS

In order to obtain experimental design data, and to provide a series of valves for laboratory use on different wavelengths, a range of experimental samples was made. To simplify the tools required for their manufacture the same anode diameter (5·5 mm) and cathode diameter (1·15 mm) were used throughout. A wavelength range of about 4·5 to 11 cm was covered; down to about 6 cm the number of segments was held constant at 12 and below this wavelength it was doubled to 24. In the 12-segment systems the anode structure was entirely of nickel which, however, operates above the Curie point so that its effect on the magnetic field should be negligible; confirmatory tests with molybdenum systems showed no obvious difference in performance. In the 24-segment systems molybdenum segments on nickel rings were used to obtain greater rigidity. In most of the experimental valves all the nickel parts were carbonized to improve thermal radiation though this was later found unnecessary for the input ratings required.

Table 1

Experimental type	Anode length (inside rings)	Segment length (see Fig. 1)	No. of segments	Wave-length (approx.)	H (oersteds)	V_A (volts)
	mm	mm		cm		
ZA	13·5	11·2	12	10·7	400	240
A	10·2	10·4	12	10·0	440	290
AB	10·2	10·0	12	9·5	460	300
B	10·2	9·6	12	9·2	480	330
C	10·2	8·0	12	8·0	550	400
D	10·2	7·2	12	7·0	600	540
DE	6·8	6·2	12	6·5	650	600
E	6·8	5·6	12	6·0	700	740
F	5·1	4·8	24	5·0	540	400
FG	5·0	4·2	24	4·5	600	550

Anode diam. 5·5 mm. Cathode diam. 1·15 mm.

Table 1 shows some representative data obtained from these valves. Outputs were about 0·5 watt and 0·1 watt from good samples, at the longest and shortest wavelengths respectively, with inputs of about 10 and 6 watts.

Fig. 2 shows the relationship between "free" wavelength (i.e. unaffected by the output coupling) and segment length, in a series of valves in which nothing else was varied. The relationship is nearly linear except when the free segment ends almost reach the opposite ring. Outside this region the ratio of wavelength to segment length, which is everywhere near 10, slowly increases as the segments are made shorter. Other tests have confirmed that for a given system, changing the amount of overlap of the two sets of segments has little effect on the wavelength until the end-capacitance effect just mentioned becomes appreciable. As the overlap is increased still further so that the free ends of the segments project through the opposite rings, the wavelength decreases again quite rapidly, tending presumably to little more than 4 times the segment length as the distance between the rings tends to zero.

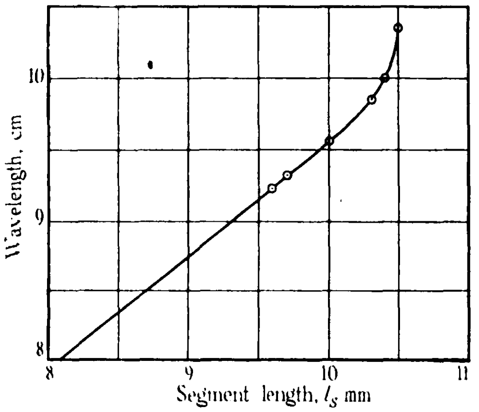

Fig. 2.—Relationship between wavelength and segment length.

Anode length (inside rings)	10·2 mm
Anode diameter	5·5 mm
Cathode diameter	1·15 mm
Number of segments	12
Segment width	1 mm
Gap width	0·44 mm

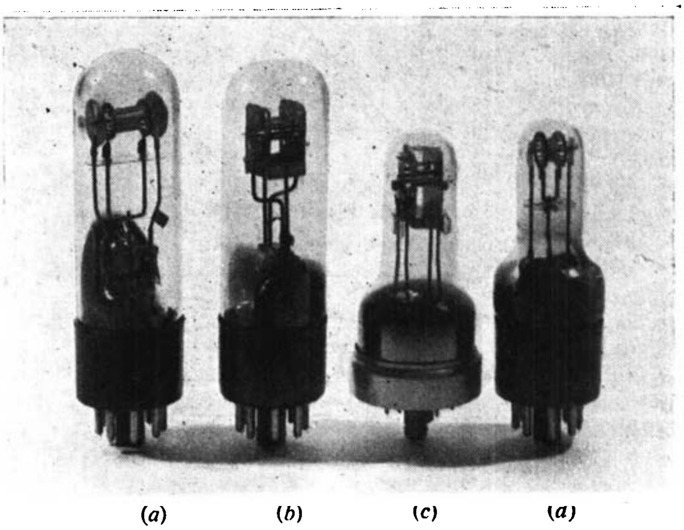
(a) (b) (c) (a)

Fig. 3.—Low-power resonant-segment magnetrons.

(a) Early B
(b) E1210
(c) CV79
(d) FG

Fig. 3 (a) and (d) shows two valves from this experimental series. Of the valve types in Table 1 several were used in measuring equipment of various kinds, but only types B and DE were developed into established designs and made in appreciable numbers. The former went into laboratory experimental production as the type E1210 and the latter became the Service types CV79 and CV89 which were produced in large quantities in the factory. These types are discussed in more detail in the next Section.

(4) PERFORMANCE OF ESTABLISHED TYPES

(4.1) Type E1210

(4.1.1) Operating Conditions.

This valve is essentially the same as the original experimental type B of Table 1 (without output leads), apart from minor modifications which were made in order to simplify the manufacture and secure greater uniformity when the valve was required in larger numbers. Fig. 3(b) shows the valve in its latest form.

As a c.w. oscillator the valve has been operated under two alternative sets of conditions, one requiring a magnetic field of about 450 oersteds and the other about 600 oersteds. The lower field condition has been more generally used and most of the data presented here refers to this, but the general form of the characteristics will apply to either condition. The valve is always adjusted to zero field angle, i.e. with the axis of the anode parallel to the direction of the magnetic field, since this is a necessary condition for efficient operation. The per-

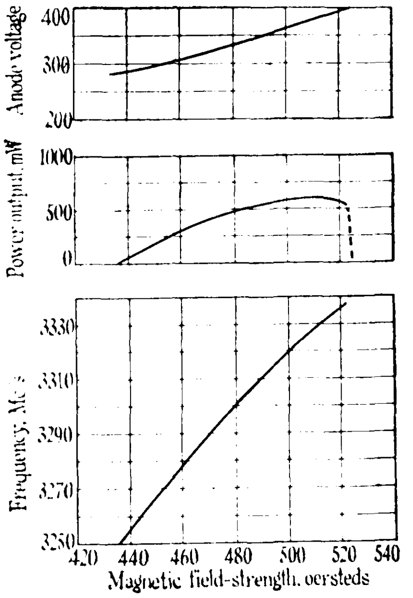

Fig. 4.—E1210 field-strength characteristics at $I_a = 25$ mA.

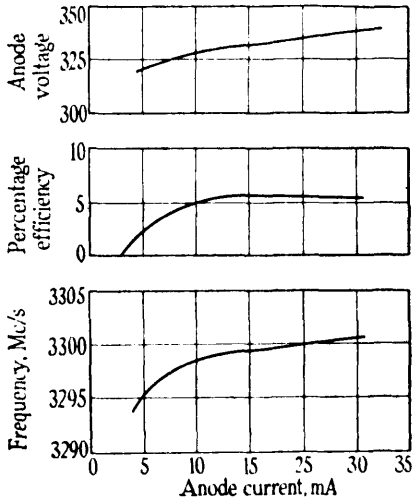

Fig. 5.—E1210 anode-current characteristics at $H = 480$.

formance can be explained by two sets of characteristics obtained on an average valve and shown in Figs. 4 and 5. Fig. 4 shows the dependence of frequency, power output and anode voltage at constant anode current on the applied magnetic field. The power output increases with field-strength to a flat maximum at about 500 oersteds and there is a relatively sharp drop out of oscillation if the field is increased appreciably above this value. Fig. 5 shows the variation of frequency, efficiency and anode voltage with anode current at a constant applied field of 480 oersteds. It can be seen that the efficiency is dependent on anode current but tends to become constant when the current reaches a value of 20 mA. The shape of the frequency characteristic is due to the combination of the electronic frequency change with that due to the thermal expansion of the anode system. With increasing anode current these effects tend to neutralize each other and the frequency becomes practically independent of anode current. When rapid changes of anode current take place the frequency changes are purely electronic and in this case there is a more or less linear increase of frequency with current with a slope of about 1 Mc/s per milliamp.

A further set of curves in Fig. 6 shows the effect of variation of field angle on power output, anode current, and frequency when the valve is oscillating in a typical circuit at constant field. Maximum output can be obtained only when the valve is set fairly accurately to zero field angle. In practice provision is made for rotating the valve with respect to the field and the zero field angle condition is obtained by adjusting to minimum anode current, or maximum output, whichever is more convenient.

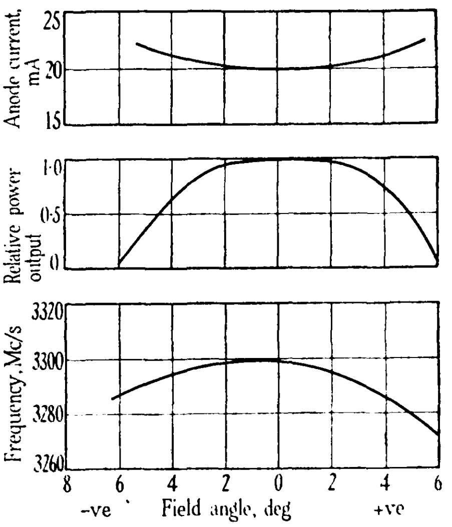

Fig. 6.—E1210 field-angle characteristics at $H = 480$.

Typical operating conditions for an average valve at fixed values of magnetic field are as follows:—

Optimum magnetic field strength (oersteds) ..	480	630
Anode voltage	330	550
Anode current (mA)	25	18
Power output (W)	0·5	0·7
Frequency (Mc/s)..	3 300	3 120

The maximum safe anode dissipation is 10 W and the heater rating is 6·3 V 0·25 A.

In pulse operation the peak anode current, for the same mean anode dissipation, is many times greater than that permissible on c.w. In general therefore the requirements of magnetic field and anode voltage are different under pulse conditions from those with c.w. operation except in the case of relatively long pulses occupying an appreciable fraction of the total recurrence period, i.e. high conduction ratios. The E1210 has been operated under pulse conditions at an optimum magnetic field-strength of 800 oersteds with a peak anode current of 400 mA and peak anode voltage of 900 V. In this condition it gives a peak output of 25 W, the efficiency being of the order of 6% which is about equal to that obtained on c.w. For higher peak currents a few experimental valves have been made with cathode diameter increased to 2 mm. On a sufficiently low conduction-ratio pulse this type gave a peak output of the order of 150 W at a magnetic field of 1 200 oersteds with a peak anode current of 800 mA and peak anode voltage of 1 300 V. This corresponds to an efficiency of 18% and is a considerable increase over that which can be obtained on c.w., with low values of anode current and magnetic field.

(4.1.2) Description of Circuit Arrangements.

The type of circuit used with this valve is shown in Fig. 7. The guide is a rectangular brass box, having an internal cross section of $3 \times 1\frac{3}{16}$ in. The valve projects into the guide with its anode system at the centre of the guide and with the axis of the anode parallel to the shorter dimension. The valve radiates directly into the guide and excites an H_{01} wave. Power is taken out by means of a conductor placed across the centre

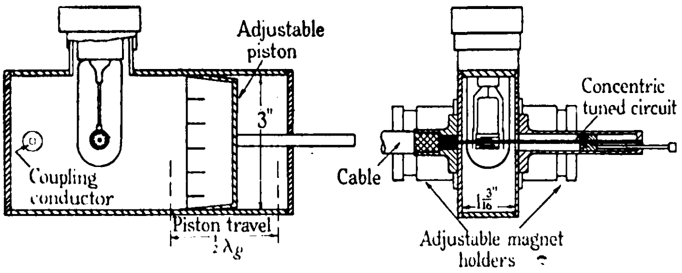

Fig. 7.—E1210 wave-guide circuit with concentric output.

of the guide, parallel to the electric vector. This conductor feeds directly at one end into a 75-ohm concentric cable, the other end being provided with a tuned concentric line circuit for adjustment of matching. The piston termination is arranged to be adjustable through a distance equal to one half the wavelength in the guide (λ_g), in order to act as an additional matching and tuning adjustment. In place of the coaxial-line output the power can be transmitted down a continuation of the guide by removing the piston and replacing the short-circuiting piston S with some form of stub or diaphragm matching device.

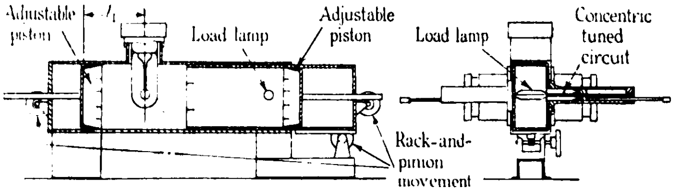

Fig. 8.—E1210 wave-guide circuit with lamp load.

In another type of circuit shown in Fig. 8, the power sink is in the same cavity as the magnetron. This arrangement has been used for the measurement of the power output of the E1210, the power sink in this case being a small tungsten-filament lamp. To cover a wide variety of matching and tuning conditions, in addition to variable end pistons in the guide and concentric stubs on the lamp, the guide is in two portions, one sliding inside the other so that the separation of the magnetron and load lamp can also be varied. The power output of the magnetron is determined by measuring the change of resistance of the load lamp after adjustment of the matching has produced maximum power transfer to the lamp.

Permanent and electromagnets have been used to produce the modest magnetic field-strengths required for the E1210. A disadvantage of the electromagnet is the necessity for well smoothed and stabilized d.c. supplies. Permanent magnets can be of the horseshoe type or may consist of pairs of cylindrical bar magnets. For variable fields the latter type of magnet system is arranged so that the gap width can be adjusted over a small range. Alternatively a special form of horseshoe magnet which consists of two limbs hinged together, so as to permit variable separation of the poles, may be used. The proportions of the magnet system are chosen to give reasonable uniformity of field over the anode cross-section. A method of obtaining the variation of field without recourse to mechanical adjustment of the magnet system is to superimpose a weak variable electromagnetic field on a fixed permanent magnetic field. This, of course, requires a well smoothed and stable d.c. supply, but the current is much smaller than that required when the total field is produced electromagnetically.

(4.1.3) Tuning.

The E1210 can be tuned over a limited range of frequency by variation of either the applied magnetic field-strength or the reactance of the external circuit. Both these adjustments involve some reduction of available power and the tuning range is therefore dependent on the amount of power required from the circuit. Change of field-strength causes the anode current to vary but by using a fairly large resistance in series with the anode, as described later in this Section, the variation can be kept sufficiently small.

The reactance of the external circuit when the magnetron is radiating into a wave guide can be adjusted by a change in position of a short-circuiting piston. For instance, in the wave guide shown in Fig. 8 the closed end of the guide formed by the piston at distance l_1 from the magnetron acts as a reactance in shunt with the magnetron. Variation of position of the piston through a distance corresponding to half the wavelength in the guide pulls the frequency of the magnetron through a range of values and back to its initial value, at the same time causing the coupling to the load to vary through a complete cycle. In Fig. 9 typical curves are shown of frequency and power output against piston setting l_1 for an average valve operating on c.w., for different values of magnetic field-strength. These curves indicate a total frequency range of about 3·5% with the output falling to 50 mW at the extremes of the range, when both magnetic and circuit tuning are employed.

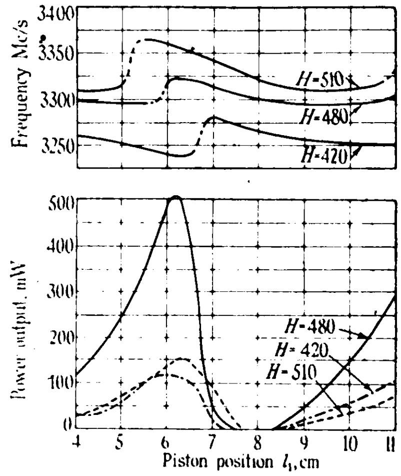

Fig. 9.—E1210 tuning characteristic.

(4.1.4) Frequency Stability.

The principal factors affecting the stability of frequency of the E1210 are temperature rise of the electrode system as the valve warms up after switching on and fluctuation of anode voltage consequent on mains-supply variations.

The amount of frequency change due to temperature effect alone for an average valve on c.w. is shown by the curve of Fig. 10. The greater part of the drift takes place in the first two or three minutes and after this interval the frequency is within 2 Mc/s of its final value. The remaining drift is almost certainly an external circuit effect due to change in circuit pulling with temperature change of the wave-guide. The amount of frequency change which takes place when the mains voltage varies will depend on the internal resistance of the anode h.t. supply. The magnetron in its oscillating condition has a very low slope resistance and to prevent small changes of mains voltage giving rise to excessive variations of current and frequency it is usual to increase the internal resistance of the h.t. supply, by inserting series resistance until it is much greater than the slope resistance of the magnetron. For the E1210 on c.w. operation a resistance of 5 000 ohms has been used and with

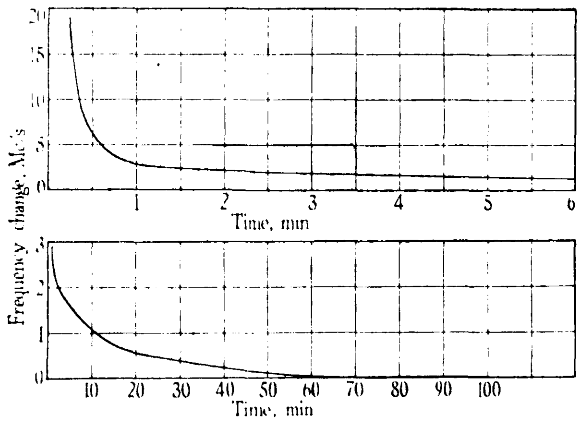

Fig. 10.—E1210: change of frequency with time after switching on.

this amount of stabilization the frequency change for ± 10% change in mains voltage is reduced to the order of ± 4 Mc/s at full load, falling to ±1 Mc/s at light load, at the optimum value of magnetic field. More drift occurs at lower values of field-strength so that a greater degree of stabilization is desirable if the magnetic field is to be variable. Frequency variation with heater voltage is negligible so long as the heater voltage is maintained within the range 5·5 to 7·5 V which is necessary in any case for normal operation.

(4.2) CV79 and CV89

(4.2.1.) Operating Conditions.

These valves are developments of the experimental type DE of Table 1. The original design has had to be modified mechanically to suit it to the factory production methods necessary on account of the large quantities required. Fig. 4(*c*) is a photograph of the CV79, showing the modified glass bulb and the ring-seal glass base. The CV79 and CV89 are identical apart from a small difference in the length of the anode segments, consequent on the small frequency separation requirement. They are used under pulse conditions, but the pulses are relatively long, occupying approximately one third of the recurrence period so that the conditions are similar to those for c.w. The lowest field which gives a useful output is in the region of 600–700 oersteds and the valves are operated in this condition in the service application for which they were designed. The performance of an average CV79 is shown in Figs. 11, 12, 13. These characteristics are generally similar in form to those already given for the E1210. One noticeable difference is the relatively sharper optimum of power output, etc., with field angle. This necessitates more accurate adjustment of field angle than is required for the E1210. Typical c.w. operating conditions are:—

Optimum magnetic field strength (oersteds) ..	650
Anode voltage	620
Anode current (mA)	12
Power output (W)	0·3
Frequency (Mc/s)..	4 600 approx.

The maximum safe anode dissipation is 8·5 W and the heater rating is 6·3 V 0·2 A. The pulse condition only differs from c.w. in that the anode current is approximately three times and the power output rather more than three times the c.w. values given above, the efficiency increasing slightly with increasing anode current.

(4.2.2) Description of Circuit Arrangements.

The CV79 and CV89, like the E1210, are intended for direct excitation of a wave guide. For experimental work a rectangular 1$\frac{3}{4}$ × $\frac{7}{8}$ in has been used. This is sufficiently above cut-off dimensions to bring the wavelength in the guide down to a reasonable value and at the same time is not large enough to

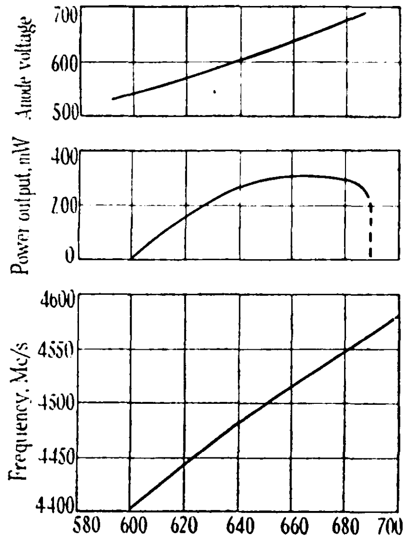

Fig. 11.—CV79/89 field-strength characteristics at I_a = 10 mA.

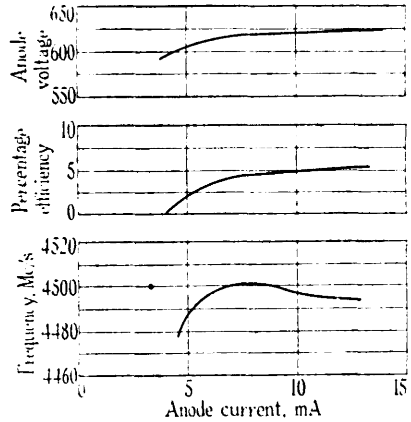

Fig. 12.—CV79/89 anode-current characteristics at H = 650.

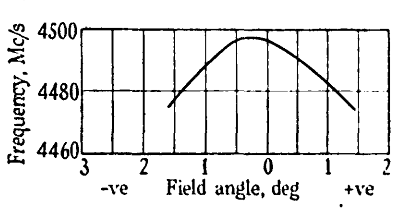

Fig. 13.—CV79/89 field-angle characteristics at H = 650.

permit the excitation of higher-order modes of the guide. Apart from this reduction in wave-guide size the circuits used with these valves have been similar to those described for use with the E1210.

Owing to the critical field angle characteristic the CV79 and CV89 are much more sensitive to change of position in the magnetic field than the E1210, since available fields are not perfectly uniform. It was for this reason that the 9-pin ring-seal base was adopted since it provides a larger and more accurate seating than the octal base. In addition it allows the valve to be rigidly fixed in position by means of a clamping ring which can be screwed down on to the metal rim of the base.

Somewhat larger magnets are required and more attention has been paid to uniformity of the field. Considerable improvement has resulted from the use of mild-steel pole-pieces having a circular recess at the centre to reduce the tendency for the field to concentrate at the centre of the poles.

(4.2.3) Tuning.

Tuning is accomplished by variation of the applied magnetic field and the reactance of the external circuit as already described for the E1210. The field can be varied over a range of approximately 600 to 700 oersteds and this, with circuit tuning, provides a tuning range of about 4%, with power output falling to 50 mW at the extremes of the range.

(4.2.4) Stability.

The magnitude of the frequency drift with time is of the same order as that obtained on the E1210. In operational use drifts of this order are compensated by automatic frequency control in the receiver. In pulse operation a series stabilizing resistance in the h.t. supply is not necessary, since the constant-current characteristic of the pentode valve which applies the pulses to the anode of the magnetron, has the same effect.

(4.3) Modulation

On c.w. operation the steady d.c. voltage required at the anode can be obtained from the usual type of h.t. rectified power supply, due regard being paid to stabilization and smoothing. The smoothing must be adequate to restrict the amount of frequency modulation, consequent on the ripple in the anode voltage, to a negligible value. For most applications two sections of conventional choke-condenser smoothing are required reducing the ripple voltage to about 0·1 V. The amount of series resistance introduced into the h.t. supply to stabilize the anode current against changes in mains voltage is a compromise between the degree of stability required and the voltage drop which can be tolerated. A smoothed rectified d.c. supply is preferable to raw a.c. on the heater as the alternating magnetic field of the heater gives rise to some frequency modulation. A bridge type selenium rectifier with a 2 000-μF condenser across the output has given sufficient smoothing for most applications. A circuit diagram of an E1210 power supply is shown in Fig. 14.

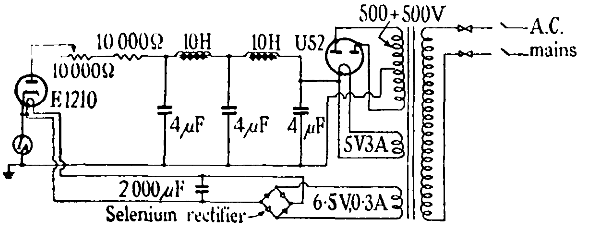

Fig. 14.—E1210: power-supply circuit.

Amplitude modulation of the output of a magnetron by applying the modulating voltage to the anode gives rise to distortion, because the h.f. amplitude is not a linear function of the modulating voltage. There is, in addition, considerable frequency modulation of the carrier and this causes further distortion at the receiver unless the band-width of the receiver is made unduly wide. To avoid these difficulties pulse-width modulation has been employed.* In this system the magnetron is switched from the non-oscillating condition into the oscillating condition at a supersonic frequency. During the oscillating pulse the anode voltage is maintained constant at the value required for oscillation and the magnetron oscillates at constant output and frequency. Between the pulses of oscillation the anode voltage is maintained below the threshold value for oscillation. Modulation is effected by varying the duration of the oscillating pulse.

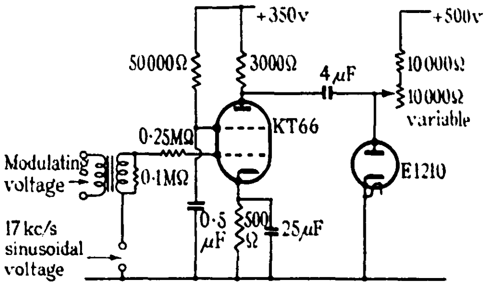

Fig. 15.—E1210: pulse-modulator circuit.

Fig. 15 illustrates a modulator circuit based on this system and used in equipment designed for the type E1210 magnetron. The modulator valve is a KT66 tetrode which is resistance-capacitance coupled to the magnetron. A sinusoidal voltage with a frequency of 17 kc/s and having an amplitude much greater than the grid base of the KT66 is applied to the grid circuit of this tetrode, producing in its anode circuit a close approximation to a rectangular waveform with an on/off ratio near unity. The modulating voltage is fed into the grid circuit in series with the sinusoidal voltage and has a peak value comparable with that of the sinusoidal voltage. The effect of this is to produce a variation in the duration of the pulses at the anode proportional to the instantaneous value of the modulating voltage. The variable-width pulses are passed to the magnetron anode through the resistance-capacitance coupling and are superimposed on the steady d.c. anode voltage, thus switching the magnetron in and out of oscillation at a recurrence rate of 17 kc/s, the duration of the oscillating pulses varying about a mean value of 30 microsec.

With this value of recurrence audio frequencies up to about 5 kc/s can be transmitted and high levels of modulation can be obtained without material distortion provided that the pulses are reasonably square. For minimum distortion at large modulation percentage it is preferable to use a triangular, instead of sinusoidal, driving voltage on the modulator grid. Even without this the system, using relatively simple apparatus, makes possible radio telephony at centimetre waves with quality comparable with that obtainable at longer wavelengths.

In more recent work on the type E1210 the possibility of making use of the frequency modulation which results from anode-voltage variation has been investigated. Since linear frequency deviations up to ± 1 Mc/s with ± 1 mA change in anode current are obtainable, a frequency modulation system based on deviations of a fraction of a megacycle, with negligible amplitude modulation, is easily realized, given adequate stabilization of the mean frequency. The chief difficulty is to prevent

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* Cf. VON LINDERN: *Philips Transmitting News*, 1935, **2**, p. 9.

unwanted frequency modulation due to spurious voltages and stray fields; in particular, a considerably greater degree of smoothing of anode and heater supplies is required. Practical tests have shown that centimetre-wave magnetrons can be used in a frequency-modulation system of this type, but the apparatus is rather more elaborate than that required for the pulse system, in spite of the very small modulating power required.

(5) APPLICATIONS

As already noted in Section 1, the use of these valves as local oscillators in receivers was one of the applications chiefly in mind when they were first developed. Their use in this field has, however, been limited, especially as compared with the reflex velocity-modulation valves which have been generally used in centimetric radar receivers since 1940, by a property which is liable to be a serious nuisance in Service equipment. This is that in these, like all other magnetrons, weak oscillations independent of any external resonant circuit can be, and usually are, generated in the space charge between the anode and cathode. In a receiver these oscillations or their harmonics, although very small in amplitude compared with the normal oscillation maintained in the resonant system, can appear as spurious signals, lightly modulated in frequency by any residual ripple in the supply voltages, and can beat with the normal oscillation in the same way as a desired signal. The effect is commonly that of a signal some 10–30 db above the receiver noise level. For experimental use it is quite easy by suitable choice of operating conditions to remove the interference from any particular frequency on which it is desired to receive, but the disadvantage of a requirement of this sort for Service use is obvious. Later work showed that, provided care was taken to maintain symmetry in the electrode system and suitable values of voltage and magnetic field were used, a simple adjustment of the angle between the electrode axis and the magnetic field removed the difficulty and that this adjustment, once made, normally held for some thousands of hours.

The use of the valves as low-power transmitters has proved simple and effective, particularly with pulse modulation; recent measurements indicate that their use with frequency modulation also has attractive possibilities although care is necessary to reduce ripple in the supply voltages to a low level.

A very simple 9-cm transmitter was built on these lines in 1941 for propagation measurements. It provided a 1 000-c/s tone signal for measurement and 17 kc/s width-modulated pulses for telephony. This was probably the first application of modulated-pulse technique to centimetre-wave equipment.

In equipment described elsewhere* which was subsequently designed for long period measurements in this field, the E1210 magnetron was used as a transmitter and as a local oscillator on about 9 cm, and the CV89 likewise on 6·5 cm. Much data on the behaviour of the E1210 has been obtained in this equipment. In particular, the valve has shown itself capable of giving continuous service over long periods with satisfactory output and frequency stability. The life is equal to that normally obtained with oxide-coated receiving valves and individual lives of 10 000 hours are frequently recorded, failure being generally due to evaporation of the oxide coating of the cathode.

Following demonstrations of the effectiveness of the early 9-cm equipment as a compact means of radio-telephone communications, in which high directivity provided a considerable degree of secrecy, the CV79 and CV89 were adopted by S.R.D.E., Ministry of Supply, in the transmitter of the Army Wireless Set No. 10. In this equipment an interlaced system of pulse modulation is used for multi-channel telephony. In the high-frequency parts of the equipment considerable use was made of techniques evolved during the development and early application of the valves described here.

(6) ACKNOWLEDGMENT

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* ARCHER-THOMSON, H., and HICKIN, E. M.: "Radio Technique and Apparatus for the Study of Centimetre-Wave Propagation," *Journal I.E.E.*, 1946, Part IIIA, p. 1367.