THE HIGH-POWER PULSED MAGNETRON: A REVIEW OF EARLY DEVELOPMENTS*

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SUMMARY

After outlining the main trend of magnetron development before the war, with particular reference to the factors which played a part in its rapid progress during the war, the paper describes the events leading to the development, in June 1940, of the first high-power pulsed magnetron for a wavelength of 10 cm.

The multi-resonator system developed by Randall and Boot at Birmingham University and the large oxide cathode developed by Gutton in Paris for a different type of magnetron were combined in a construction, designed for use with a small permanent magnet, which met the requirements for airborne service and was suitable for quantity production. The result of these steps was an immediate increase in pulse power and life by a factor of at least 10, with a similar reduction in magnet weight.

The systematic development of design procedures, based on pre-war work, played a major part in the 100-fold increase in pulse output power at 10 cm, which was achieved between June and December 1940. The fundamental difficulties of multi-segment magnetron design were, however, only beginning to be appreciated at the end of this initial period of rapid expansion and, by comparison with modern knowledge, the ideas of that period and the technique available for experimental study were very incomplete. A companion paper provides a review of some of the vast amount of work which still remained to be done after the close of the phase with which the present paper deals.

(1) THE PRE-WAR BACKGROUND

The magnetron as a generator of very high frequencies is already twenty-two years old. In 1924 Žáček showed that in its simple diode form it could produce oscillations analogous to those found by Barkhausen in positive-grid triodes; and in the same year Habann, in an academic study of methods of producing negative resistance characteristics without secondary emission, introduced, as one of a variety of possible electrode systems, the split cylindrical anode. A few years later the publication in America of the Japanese work, particularly by Okabe who used the split anode system to generate centimetre waves, attracted attention for the first time to the practical possibilities of the device. When the present author presented the results of the first study of the subject in this country before The Institution in 1933 the literature comprised a dozen papers; by 1939 it had multiplied more than tenfold (cf. Harvey, "High Frequency Thermionic Tubes," Chapman and Hall, 1943). Unfortunately the published art did not gain as much in clarity as it did in volume and the real difficulties were added to by the tendency to postulate new "types of oscillation" to explain fresh facets of the subject as they were revealed by successive investigations. While there is much that is still not understood, even in the simplest of magnetrons, it is probably true that there is no need to invoke any processes of oscillation maintenance different from those recognizable in the Japanese work of the late 1920's in order to account for all the practically significant results between then and the present day.

By early 1933 the main characteristics of two clearly distinct kinds of oscillation, the "electronic" oscillations found by Žáček and the frequency-independent negative-resistance oscillations of Habann, were known. Some peculiar characteristics had been observed in the practically important region near the short-wave limit of the "dynatron" oscillations in two-segment magnetrons, but it was only after experimental proof had been obtained a few months later of the cause of cathode bombardment that the significance of electron energy changes in transit began to be adequately appreciated. It was soon found that the behaviour near the short-wave limit could not be explained as a gradual falling off in performance with increasing transit angle (as some investigators were still trying to explain it several years later) for the simple reason that with fixed operating conditions the efficiency actually increased, as the limiting wavelength was approached, to values higher than could be accounted for by the static characteristics.

Four-segment magnetrons were described in the early Japanese work, and a 12-segment system was tried, unsuccessfully, in 1932 by the author—with the idea that, if Hull's second solution giving circular orbits for the steady state were correct, very high frequencies might be obtained by reducing the inter-segment distance. Posthumus' successful development of the 4-segment magnetron in 1934–35 and the "rotating field" theory by which he explained its advantage over a similar 2-segment system was, however, an outstanding contribution and one which anticipated some of the results of recent theoretical work. There was, however, a good deal, especially in the behaviour of 2-segment magnetrons, which this theory did not account for and alternative explanations of the selective negative resistance effect were sought. It was only when the ideas of precessional resonance between the electron orbits and the standing wave of potential round the anode segments were developed by the author and by Herriger and Hülster to the point of yielding the same type of relationship between operating conditions and dimensions as that given by the rotating field theory that it was realized that the spiral electron paths of the latter were simply the mean of the looped paths to be expected in reality. Since this approach provides a very simple, if incomplete, picture of the basic mechanism of multi-segment magnetrons and formed the basis of a generalized procedure for magnetron design which was used for several years before the war it may be worth reproducing here.

An electron in crossed electric and magnetic fields will move with a mean velocity $\bar{v} = \mathscr{E}/H$ in a direction perpendicular to both fields, provided any changes in the strength of either field over areas comparable with the size of the loops performed round the magnetic lines of force remain small. For the cylindrical system of Fig. 1, $\bar{v}$ is the tangential velocity of pre-

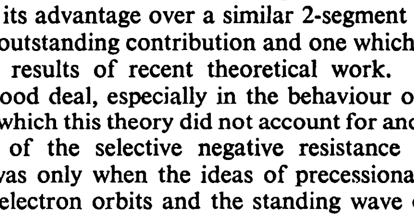

Fig. 1.—Illustrating precession of electron orbits in a cylindrical system.

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* Radio Section paper.

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cession of the orbits round the axis. The angular velocity is therefore $\Omega = \mathscr{E}/Hr$. As a reasonable approximation for space-charge limitation in the oscillating condition a linear potential distribution is assumed, giving $\mathscr{E} = V_A/(a-b)$ and $\Omega = V_A/H\ 1/r(a-b)$. Here Ω varies during the transit from cathode to anode; a mean value, half way from cathode to anode, i.e. at $r = (a+b)/2$, is therefore taken giving $\Omega = \frac{2V_A}{H}\frac{1}{a^2(1-b^2/a^2)}$

For an anode having n pairs of segments oscillating with 180° phase difference between adjacent pairs the condition for resonance is that the electrons should traverse the angle π/n subtended by one segment in the half-period $T/2$ of the oscillation, i.e.

$$\Omega T/2 = \Omega\lambda/2c = \pi/n$$

Therefore
$$V_A = \pi c H a^2\left(1 - \frac{b^2}{a^2}\right)/n\lambda$$

$$= 943 H a^2\left(1 - \frac{b^2}{a^2}\right)/n\lambda \text{ (practical c.g.s. units.)}$$

Fulfilment of this condition means, at least approximately, that "favourable" electrons, so phased as to cross a slot plane at the moment of maximum retarding field, will be cumulatively retarded at successive crossings. But where the slot potential-difference is in this sense (i.e. electron-retarding) the equipotential lines of the electric field curve outwards as the slot plane is crossed; and the relationship $\bar{v} = \mathscr{E}/H$ implies, in a uniform magnetic field, that the mean electron paths tend to follow these equipotentials.

Thus the mean paths of the retarded electrons spiral out towards the anode while those of the accelerated electrons approach the cathode. From this it can be expected that increasing the magnetic field to values much above the cut-off value H_c, and so reducing the size of the loops in the electron orbits, will tend to increase the efficiency both by allowing the favourable electrons many successive decelerations on their way to the anode and by confining the unfavourable ones more completely to the neighbourhood of the cathode.

It may be noted that for H/H_c not much above unity, so that the electronic loops nearly fill the inter-electrode space, the validity of $\bar{v} = \mathscr{E}/H$ is doubtful; experimentally V_A for maximum efficiency is then less than the value calculated above, as more accurate theory shows it should be. At the other extreme, with very large H/H_c, it appears reasonable in the limit to take the value of Ω at $r = a$ rather than at $r = (a+b)/2$; this doubles the calculated V_A, a result in good agreement with its measured value for 2-segment valves at large H/H_c when the oscillation amplitude is limited to small values. A further experimental result of some interest is that reducing the cathode emission below the minimum value for space-charge limitation increases the value of V_A required. This would be expected from the reduction in Ω as the potential distribution approaches the logarithmic form for cylindrical electrodes without space charge.

The resonance relationship, or the more accurate threshold relationship given in Section 6.2 of the accompanying paper,* can be used to produce generalized magnetron operating data in several different ways. One of these, which has the advantage of being independent of b/a, is illustrated in Fig. 2(*a*). Combining this relationship with the cut-off condition shows that the minimum wavelength (zero efficiency) corresponds to a constant value of $n\lambda H(1 - b^2/a^2)$ or of $n\lambda V_A^{\frac{1}{2}}/a$. It was expected, and confirmed by measurements on 2- and 4-segment valves with filament cathodes (subject to some experimental restrictions), that these expressions would also be approximately constant for any fixed value of efficiency; Fig. 2(*b*) illustrates this. The dotted curve in Fig. 2(*b*), which applies approximately to modern multi-segment large-cathode magnetrons, has been added for comparison. Possible reasons for the difference will not be discussed here, but it is not attributable to circuit losses. It is of considerable interest to note that the best results for early 4-*segment* valves with *central* filament (see below) fall close to the lower part of the dotted curve.

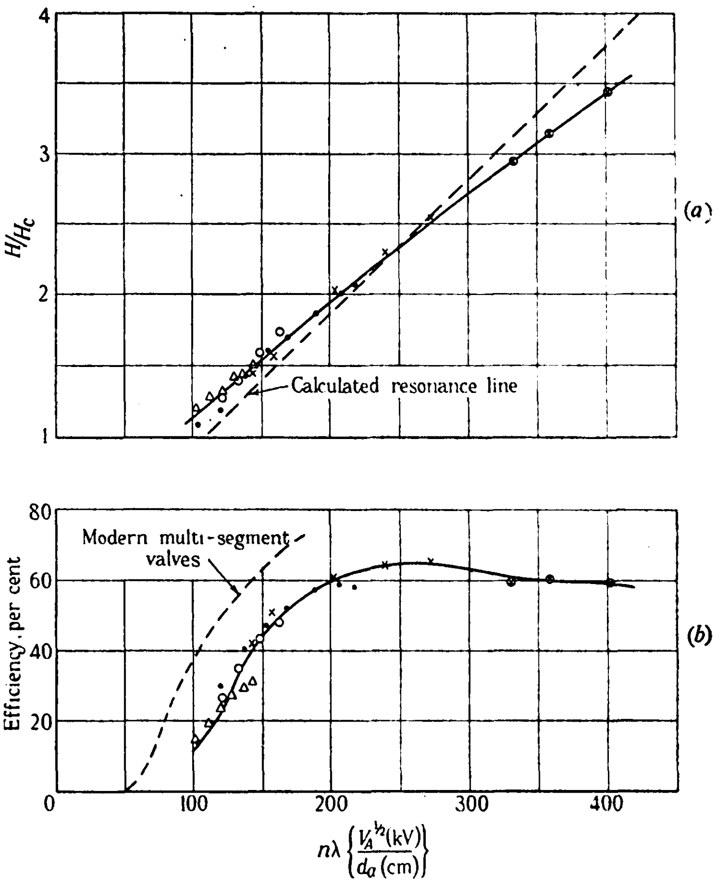

Fig. 2.—Generalized operating characteristics.

4-segment magnetron type E880 No. 631.
$n = 2$. $d_a = 2a = 0{\cdot}7$ cm.
Cathode diameter $= 2b = 0{\cdot}025$ cm (thoriated tungsten).
Cathode eccentricity 12%.
Anode voltage 200–1 000 V.
Magnetic field 300–1 950 oersteds.

Wavelength (cm)	
50	△
60	○
76	●
100	×
150	⊗

Almost all the magnetrons of the pre-war period used tungsten-filament cathodes, which were quite adequate for the early experimental c.w. requirements; in the days when variable high-voltage d.c. supplies were inconvenient and expensive it was even considered an advantage to be able to limit the input by reducing emission. German data on the effect of large-diameter spiral tungsten filaments indicated a drop in efficiency with increasing cathode diameter, especially in 4-segment valves, and this misleading result was widely believed.

Trials of oxide and thoriated-tungsten cathodes in the early 1930's gave bad results on life in the heavily-loaded radiation-cooled structures which had been established for pure tungsten filaments; the problem was solved in 1937 for thoriated tungsten, and this technique was used in the E880 (NT75) to meet the requirements of one of the earliest Service applications of magnetrons.

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* See page 991.

This restriction of established practice to small cathodes was also related to the general conclusion that the use of more than 4 segments was of little practical value; together they formed a kind of vicious circle which prevented the combination of many segments with large cathodes, now so obviously desirable for the shortest wavelengths, from following as a natural consequence from the earlier work. The fundamental point was simply that with a small cathode there is a large reduction in the oscillating tangential field near the cathode in a 4-segment as compared with a 2-segment system with the result that in the former, except at small values of H/H_c, the optimum load impedance is high and the starting of oscillations difficult. Although Posthumus' fortunate discovery that eccentricity of the filament in the anode (or less satisfactorily, of the valve in the magnet) obviated this difficulty at the price of an increase in minimum wavelength, 4-segment valves remained more difficult to make with uniform characteristics than 2-segment ones. The few studies that were made with more than four segments, and particularly with six, indicated an increase in these difficulties. There is little doubt that such valves could have been made with central filaments to cover a relatively small wavelength range with rather low efficiency; but they would not have appeared attractive at a time when useful ranges of one or two octaves and efficiencies of the order of 50% were regarded as normal requirements, with the "electronic" oscillator in the background as a wide-range low power source for the shorter wavelengths.

The performance, reported in 1938 by Gutton and Berline, of the first successful multi-segment valves—still with tungsten filaments—was, in fact, of the sort just indicated, i.e. rather low efficiency with little tuning range. The anode segments formed a fixed self-resonant system, and efficiencies of 10–15% were obtained at 10–20 cm. The most striking practical feature was that by making a large increase in the number of segments (the range covered was 6 to 18), this performance was achieved with quite low anode voltages and magnetic fields, the latter being in some cases only a third of the field which would have been required by an "electronic" oscillator. Gutton and Berline's reasons for believing, once again, that a new type of oscillation had been discovered might well have been disputed with one exception, which seemed decisive. This was that the optimum magnetic field, over a wide range of anode voltage in which the wavelength was roughly constant, was *less than* the cut-off field H_c (0·8–0·9 times). It is now believed that this result was due to an experimental error; but the apparently unavoidable conclusion that the behaviour of multi-segment magnetrons could not be predicted from the well-established facts for 2-segment and 4-segment systems had a profound effect on our early ideas about high-power centimetre-wave magnetrons.

A tentative explanation of these results, in which the idea of the fields of the slots acting as a succession of cylinder lenses was invoked to explain the possibility of long electron paths close to the anode under sub-cut-off conditions, was discussed with Gutton and Berline during a visit to Paris in 1939. The mechanism was here again regarded as one of successive retardation of favourably-phased electrons, but in this case with a simple tangential motion close to the anode, and therefore with a velocity before retardation close to $\sqrt{[2(e/m)V_A]}$. For infinitesimal amplitude resonance occurs when the inter-segment transit time at this velocity is $T/2$ for a phase difference π between adjacent segments. If electrons describing such a path could be retarded to a standstill, about $T/4$ optimum transit time, calculated at the same velocity, would be expected; thus $T/3$ might be expected to give a useful estimate of the actual optimum anode voltage, namely:—

$$V_A = (1\,500\ \pi a/n\lambda)^2 \text{ (practical c.g.s. units).}$$

It was found in the discussion that the observed starting and optimum voltages were adequately accounted for in this way. The magnetic field was regarded simply as an auxiliary variable to be adjusted to some constant fraction of the cut-off value H_c, so giving suitably grazing electron paths.

This leads to $n\lambda H(1 - b^2/a^2) = $ const., as was found for constant efficiency in the precessional resonance case.

An important experimental point came to light during this visit. The long operating range in anode voltage was not, as had first been thought, continuous; there were, in fact, two separate ranges. In addition to the efficiency maximum near the optimum voltage calculated from the author's "tangential resonance" formula there was a second one at about 4 times that voltage; the break between the two ranges was, however, quite small. A little later it was realized that phase differences other than the 180° assumed above were possible between adjacent segments and that, in particular, a 12-segment system could behave as a 6-, or 3-segment one by re-arrangement of the phases. With $n = 3$ instead of 6 the calculated voltage agreed quite well with the observed higher optimum.

It was arranged that sample valves would be made available to the author for further study, especially of the optimum field value and of the behaviour with respect to space charge. Unfortunately, owing to difficulties which arose on the outbreak of war, this study was delayed until the following year.

In order to stress, in the limited space available, some of the factors which played a part in later developments much work of general interest has had to be ignored in this introductory survey. Among problems of great physical interest there is the work, notably of Linder in America, on the anomalous electron temperature in magnetrons, and the evidence for a variety of self-maintaining internal oscillations which suggests the separate existence of radial, tangential and axial types.

On the application side typical examples are our detailed study of modulation by space-charge grids and the development of resonator frequency stabilization as a highly effective practical technique for wavelengths of the order of 50 cm; this last had in fact a direct bearing on some of the circuit problems of centimetric magnetrons. And finally, as an early indication of the shape of things to come, a test carried out with Mr. J. F. Coales of H.M. Signal School in November, 1938, may be mentioned. A pulse output of 1½ kW at 37 cm was obtained from an E821 magnetron, designed for 150 W c.w. output at 1 metre; it was concluded that no fundamental problem was involved in short-pulse operation of magnetrons.

(2) CENTIMETRE-WAVE DEVELOPMENT: THE INITIAL STEPS

It is generally known that early in 1940 an experimental high power magnetron using cylindrical cavity resonators as circuit elements was independently produced by J. T. Randall and H. A. H. Boot* at Birmingham University, and that the rapid development of magnetrons of this kind as powerful pulse generators opened up the field of centimetric radar so far as transmitter requirements were concerned. In this Section the main steps in this development and the considerations which prompted them are traced.

It will be seen that by 1938, although mistaken ideas were still current about the effect of cathode size and therefore about power-handling capacity, much of the essential background for the development of high-power pulsed magnetrons was already established. It was primarily the circuit problems for centimetre waves which remained to be solved, and it soon became clear that in solving them the normal ideas of tunable circuits external to the valve must be abandoned if high powers were to be

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* See page 928.

obtained. Internal oscillatory circuits, more or less integral with the anode segments, appeared quite early in the practical art but were rarely favoured in industrial development on account of their inflexibility. In addition to the structures with axially resonant segments, developed in multiple form by the French, the combination of the anode segments with one or more oscillatory elements, which could be regarded either as sections of low-impedance line or as open-ended cavities, can be traced from the work of Slutzkin in 1934. Many interesting variants of these, workable and otherwise, are to be found in the patent literature.* A low-power single circuit design of this type developed in 1937 for about 3 cm is illustrated in Fig. 3; and a high-power 5 cm design (Fig. 4) illustrates the combination of a water-cooled resonant segment system with a metal envelope serving as output wave guide. The stimulating effect of the development of cavity resonator techniques in the klystron, and not least the loop-and-line technique for coupling to the load, must also be noted. It was under this stimulus that Randall and Boot developed the multiple circuit copper-block structure in a practically fruitful form which provided the basic solution of the centimetre-wave circuit problem adopted for all the subsequent developments in this country and the United States.

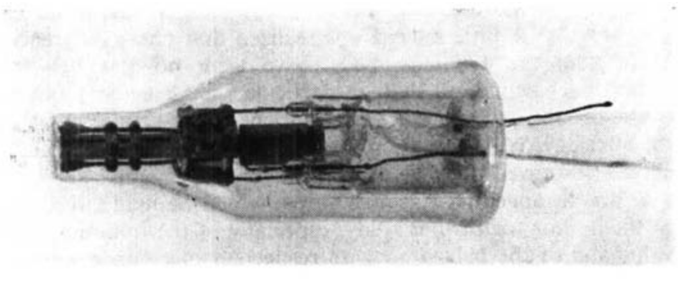

Fig. 3.—Low-power magnetron with integral anode and resonant circuit for about 3-cm wavelength.

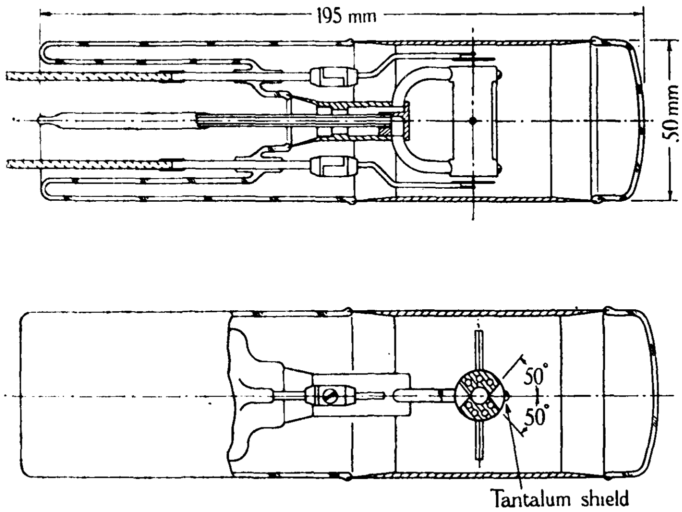

Fig. 4.—Water-cooled resonant-segment magnetron design for high-power c.w. operation at 5 cm wavelength (March 1940).

In March 1940 an urgent need arose for a pulse transmitter on about 10 cm for A.I. radar. A 4-segment glass magnetron with thoriated tungsten filament was designed, to give about $\frac{1}{2}$ kW peak directly into a wave guide with 10 kV 0·25 A input and 3 500 oersteds field. This was preferred, for the light mean loading involved, to a multi-segment design based on existing data for the supposedly different "tangential resonance" oscillations mainly on grounds of expected efficiency.

A few weeks later contact was made with the work of Randall and Boot at Birmingham University. At that time their 6-segment copper-block valve, operating on the pump, had produced about 150 watts c.w. output at 9·9 cm with 7 kV 0·15 A input. The field of 1 300–1 400 oersteds was produced by a large electromagnet with about 5 in air-gap. A 0·75-mm tungsten filament was used in a 12-mm anode, 40 mm long. Insufficient data were available to decide the type of oscillation involved but it was noted that the anode voltage agreed quite well with that calculated from the "tangential resonance" formula. In discussing the design the author suggested that it could be improved and simplified, and the magnet weight greatly reduced, by using closed metal ends for the block, in place of the original glass-to-metal seals, and side-arm seals for the cathode. A sealed-off design on these lines (Fig. 5), with some further minor improvements, was produced in collaboration with Birmingham University; this was designed to fit the $2\frac{3}{4}$-in air-gap of a standard 50-lb electromagnet. Its performance, limited by the emission and life of the tungsten filament, was similar to that of the original model and reached outputs of the order of $\frac{1}{2}$ kW. In this design the gold seal technique, developed by D. A. Boyland several years earlier, and suggested for use in the magnetron by R. le Rossignol, was introduced as a clean and simple method of attaching the copper end-discs to the block after mounting the cathode.

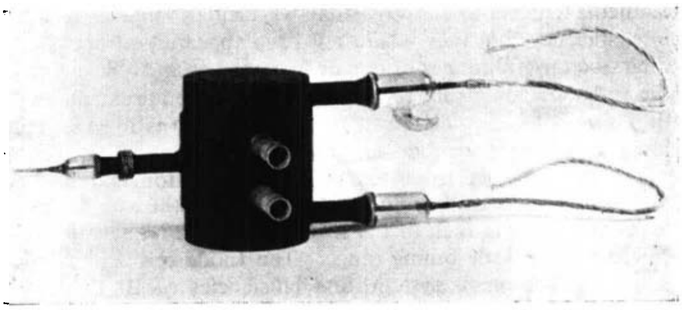

Fig. 5.—E1188, No. 1. Improved model of Randall–Boot tungsten-filament magnetron; designed and made in collaboration with Birmingham University. (Design completed 16th May, 1940.)

C.W. or pulse output of the order of $\frac{1}{2}$ kW at 10 cm. Electromagnet weight 50 lb.

At the time of the first discussion at Birmingham the chief interest in the copper-block structure, so far as the commitments of the G.E.C. Laboratories were concerned, was as a basis for high power c.w. designs for communication on rather shorter wavelengths. But with increasing pressure on the need for 10-cm A.I. it was considered whether a design using this technique could provide a lighter and more powerful pulse source than the dull-emitter resonant-segment magnetron which was already in development, with good prospects of producing as much peak power as the Birmingham valve. Both of these, as they stood, involved electromagnets which were inconveniently large for airborne use, one on account of the large gap and the other on account of the high field-strength requirement.

It was decided to attempt such a design, though it had to be based on several unproved assumptions. These were:—

(1) That the type of oscillation in the copper-block magnetron was the same as in the Gutton–Berline multi-segment valves. The main point here was that it had been concluded from the author's interpretation of the mode of

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* The earliest proposal for an anode-resonator system of the hole-and-slot type appears to be that in U.S. Patent No. 2063342 of 8th December, 1936 (A. L. Samuel). This, like subsequent similar proposals and laboratory designs, lacked a satisfactory method of coupling the resonators to the load.

operation of the latter, at the time of the visit to Paris in 1939, that the cathode diameter should have no critical effect on their behaviour and that therefore—contrary to the general belief about other magnetrons—large-diameter cathodes could be used.

(2) That efficient operation of valves of this type was possible with space-charge-limited anode current, so that increased cathode emission would make possible increased pulse output. At this time (April 1940) there was still no decisive information on this point.

(3) That the mode of oscillation of the copper-block resonant system was such that the wavelength was substantially independent of the axial length.

A design was worked out on this basis using a block with cross-sectional dimensions nearly the same as those of the Birmingham valve. But the anode length/diameter ratio was chosen to give a good compromise between power and magnet weight, the end spaces were kept small so that an existing 6-lb permanent magnet with 1½-in gap could be used, and a large diameter thoriated-tungsten spiral cathode was introduced. It was estimated that this design should give at least 1 kW peak output at about 5 kV.

At this point the samples of Gutton's 16-cm resonant segment valve, M.16 (Fig. 6), which had been promised in June 1939 were received. In the meantime it had been greatly improved by the introduction of a large oxide cathode. In spite of the author's recommendation of the use of thoriated tungsten, following his own successful experience in pre-war magnetrons, the oxide cathode had been preferred on account of extensive French experience with it in ordinary transmitting valves. These 16-cm magnetrons, which had already given pulse powers of the order of 1 kW, were brought to Wembley by Dr. M. Ponte of the Compagnie Générale de Télégraphie Sans Fil and were disclosed to us with the authority of the French Government. This was the starting point of the use of the oxide cathode in practically all our subsequent pulsed transmitting valves and as such was a significant contribution to British radar. The date was the 8th of May, 1940.

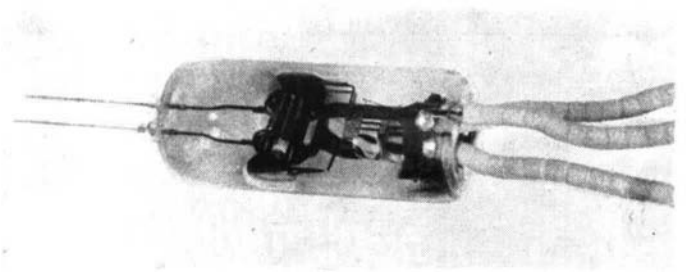

Fig. 6.—Gutton resonant-segment magnetron, type M16, with oxide cathode, for pulse or c.w. operation. (Sample received 8th May, 1940.)

Pulse output of the order of 1 kW at 16 cm.

While the first of our copper-block valves was being made, detailed c.w. and pulse tests were carried out on the M.16, the latter with an emergency modulator comprising a motor-driven commutator operating on the grid of a large pentode and giving pulses adjustable between 200 and 2 000 microsec at 50 pulses/sec, with the object of establishing general principles which we believed would be valid in our own designs. They proved, in fact, of great value.

It was concluded that the "tangential resonance" formula gave the optimum operating voltage approximately correctly, but that the optimum magnetic field was near $1\cdot2\,H_c$ (the approximate operating conditions for the Birmingham valve gave about $1\cdot4\,H_c$); and no oscillations were obtained below cut-off field. Fig. 7 shows some of the results. The two ranges of oscillation were interpreted as corresponding to "12-segment" and "6-segment" operation of the oscillatory system. The dotted curves in the lower part of the figure indicate what was probably the true interpretation in the light of later knowledge.

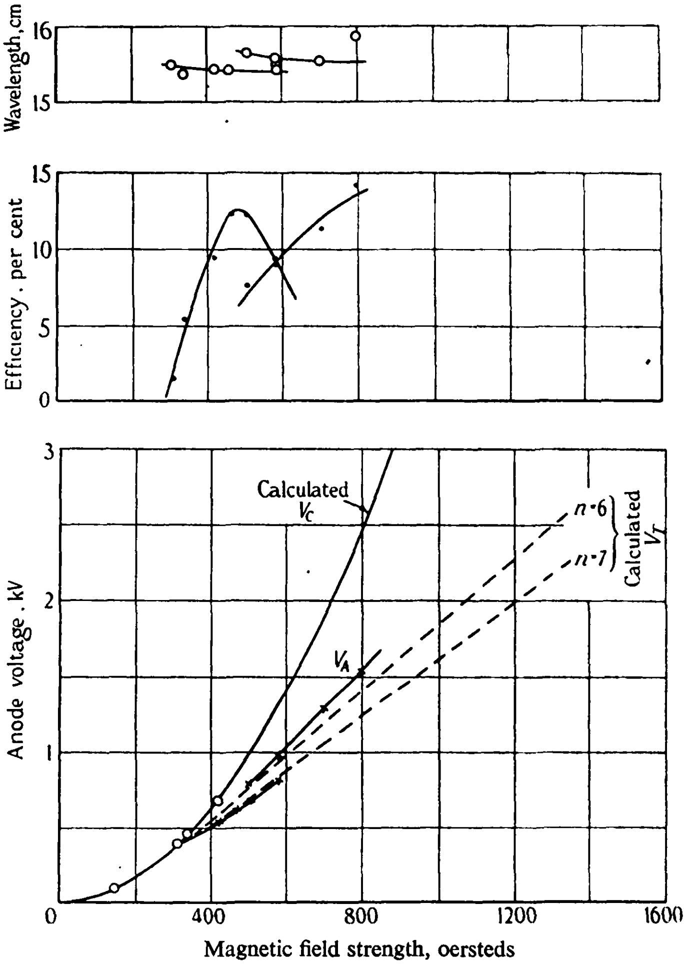

Fig. 7.—Operating characteristics of M16 magnetron.

$n = 6.$ $a = 0\cdot5$ cm. $b = 0\cdot2$ cm.

V_A for maximum efficiency.

At the lower field-strengths the output and efficiency were measured over the whole voltage range from threshold to cut-off. Hence a preliminary indication was obtained of how to estimate the anode current for maximum efficiency and maximum output, in terms of the space-charge-limited diode current I_D at $H = 0$, calculated for the operating anode voltage. These were not far from the typical figures obtained later, namely of the order of 1/20* and 1/3 of I_D respectively. This knowledge was of the greatest value in predicting the approximate operating conditions and performance of new designs. Cathode secondary emission, discovered at Wembley in 1933, appeared with the oxide cathode as a factor of major importance for the first time. It was found that oscillations could be maintained, at low anode current, with a thermionic emission less than 1/100 of that anode current. In the course of this series of measurements an attempt

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* In this connection it should be noted that the factors determining the small value of current below which the efficiency falls steeply, in a valve free from low-current mode changes and mechanical faults, have not been clearly elucidated. They are of practical importance only for c.w. applications.

was even made to detect directly the reduction in magnetic field-strength caused by the rotating cloud of electrons inside the anode. A negative result was obtained giving a very rough upper limit for the circulating current (< about 10 A with 1 A anode current, $H/H_c = 1\cdot2$).

(3) THE E1189 OXIDE CATHODE PULSED MAGNETRON

The main features of this design with its large cathode, short magnet-gap, and simple, almost all-metal, construction have been indicated above. In addition, air cooling was substituted for water-cooling. The measurements on the M16 had borne out the first two of the assumptions (possibility of large cathode and space-charge limited operation in a multi-segment valve) on which the design was based, and the tests on the first trial samples, E1189 No. 1 with the thoriated-tungsten spiral cathode (Fig. 8) and No. 2 with an oxide cathode, were awaited with some confidence—though not without speculation on the possible effect of voltages of the order of 10 kV on the oxide cathode. The last assumption (independence of wavelength on block length) was verified as soon as the first wavelength measurement was made.

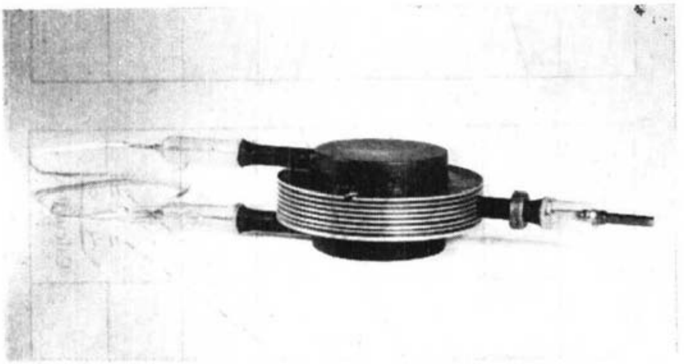

Fig. 8.—E1189, No. 1. Original design for high-power pulse operation in aircraft. (Design completed 25th May, 1940. First operated 29th June, 1940).

Pulse output of the order of 10 kW at 10 cm. (Output, with 1 000-oersted permanent magnet: 3 kW from first design and 5–10 kW from final design.)
Permanent-magnet weight 6 lb.

The main internal dimensions of these valves were:—

No. of segments $= N = 6$.
Anode dia. $= d_a = 1\cdot2$ cm.
Cathode dia. $= d_k = 0\cdot3$ cm; o.d. of spiral of 0·4 mm *thoriated tungsten* in *No.* 1; emission 5–10 A at 9 V 8 A.
0·45 cm *oxide coated* nickel in *No.* 2; emission about 5 A at 7 V 1·8 A.
(Emissions are for 1 millisec pulse.)
Anode length $= l_a = 2\cdot0$ cm.
Circuit hole dia. $= d_c = 1\cdot2$ cm.
Slot width $= 0\cdot2$ cm.
Slot depth $= 0\cdot2$ cm.

The two valves were completed together and outputs of the order of 1 kW peak at 5–40 microsec, 50 pulses/sec, were initially obtained from both, using 1 000–1 100 oersted permanent magnets (29th June, 1940). The output at 6 microsec was independent of heater voltage down to zero with the oxide-cathode sample, and its success was regarded as completely established. An early mercury-vapour triode (E1191) modulator was used. The wavelength was near 9·8 cm for both valves. Within a fortnight peak outputs of about 10 kW had been measured in a water load with an input of about 8 kV, 8 A, 30 microsec, 50 pulses/sec; the field of about 1 400 oersteds was provided by an electromagnet. With higher inputs, powers estimated at over 15 kW were obtained, but with the large pulse length used persistent flash arcs occurred at this output. The cathode bombardment power was estimated by heater resistance change in No. 2 at 5–10% of the mean input, increasing appreciably as the load coupling was reduced. This agreed with some earlier measurements on glass magnetrons. Measurements of frequency variation with operating conditions were also made with encouraging results.

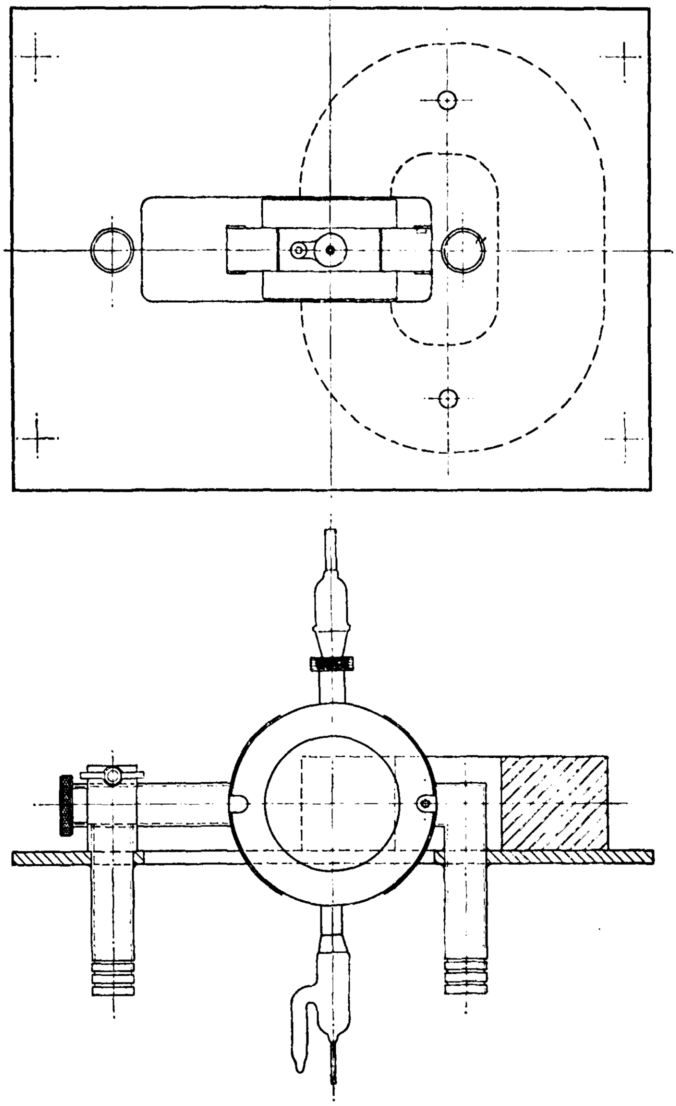

Fig. 9.—Original valve- and magnet-mounting for E1189.

Fig. 9 shows the original form of valve and magnet mounting. The Alnico permanent magnet was Messrs. Darwins' type M4735 giving an average fully-magnetized field of 1 010 oersteds in a 38-mm gap and weighing 6 lb. The external oscillatory circuit in these first tests was an adjustable length of slotted coaxial line attached to the output seal; see Fig. 10, which also shows the water load in its original form.

By the middle of July E1189 No. 1 was in use by the Wembley A.I. group, who produced an improved form of mounting and output circuit; No. 2 went to Prof. Dee's group at A.M.R.E. (now T.R.E.) a few days later. An urgent demand for further samples developed and several copies of No. 2 were made, using the chamber of a Colt revolver—which just happened to be the right size—as a drilling jig! A few experimental variants were also made to check design procedure.

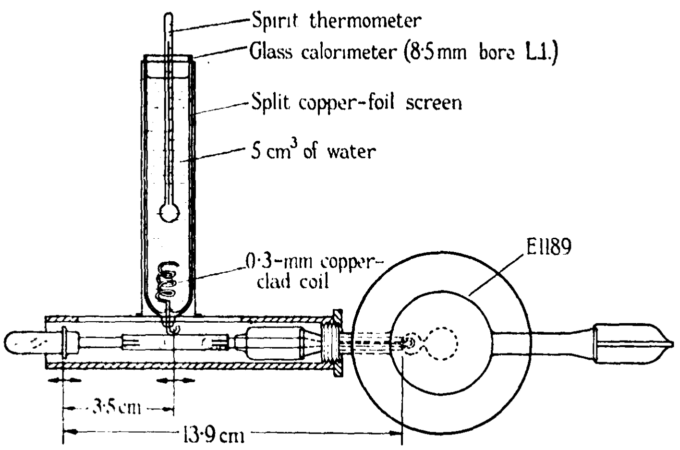

Fig. 10.—Original output circuit and water load for E1189.

During this early stage of the development the attempt was made to reduce as much as possible to a calculable basis. An elementary procedure for wavelength calculation had already been developed and worked quite well, though it was improved on later; and a somewhat dubious calculation of optimum cathode size for maximum output at constant H (giving b/a about 0·4, which was adopted) had at least the merit of giving an answer which proved satisfactory. The output coupling loop dimensions in the first samples had been kept the same as in the Birmingham valve, though the output line was modified to give a more nearly constant characteristic impedance. Calculation, from rough measurements on E1189 No. 2 of the variation of the power fed to a matched 75-ohm cable load with its distances from the coupling loop and from the open end of the output line, indicated that the equivalent generator (series) resistance at the terminals of the loop was about 100 ohms; this confirmed that the coupling-circuit constants were about right for feeding a 75-ohm load, as required. Hence, from the dimensions of the loop and the internal circuits, it was concluded that the resistance appearing across the output slot with optimum loading was about 600 ohms, that the oscillatory voltage across the slot was about half the steady anode voltage, that circuit losses probably did not exceed a few per cent, and (on rather doubtful grounds) that loading at a single circuit element would be satisfactory for many more than six elements.

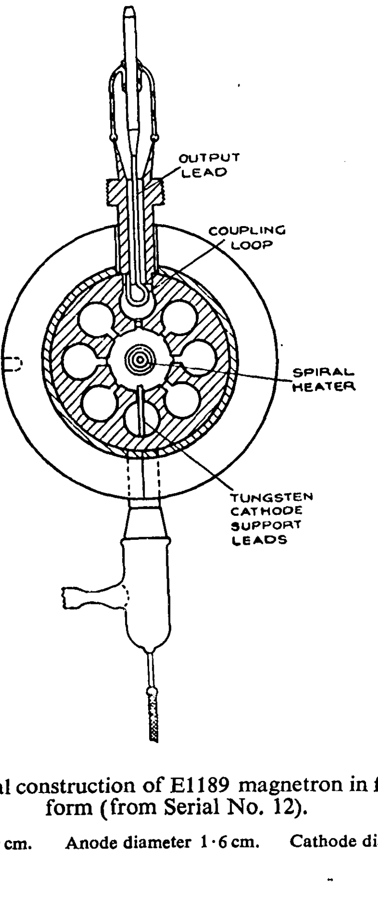

Fig. 11.—Internal construction of E1189 magnetron in final 8-segment form (from Serial No. 12).

Anode length 2·0 cm. Anode diameter 1·6 cm. Cathode diameter 0·5 cm.

As a result of these calculations and measurements it was decided that the design represented by E1189 No. 2 was satisfactory except that the field required for what appeared to be maximum efficiency was too high for the existing permanent magnet. This was corrected by re-calculating the design for eight segments instead of six, keeping the wavelength at 10 cm. Fig. 11 shows details of the modified design which was later standardized for naval use as NT98. Its variant, E1198 (CV38), was used in the first centimetric A.I. equipment on 9·1 cm. Fig. 12 shows the performance of the second sample to this modified design (E1189 No. 13); the first, No. 12, had already (August 1940) been despatched to accompany the Tizard mission to the United States.* It will be seen from Fig. 12 that the output obtained with the permanent magnet was comparable with that given by the 6-segment version with the higher field strength electromagnet. Fig. 13 shows a typical curve for an early E1198 giving the frequency change with time after switching on; after 3 minutes the frequency is within about 1 Mc/s (in 3 000) of the final value.

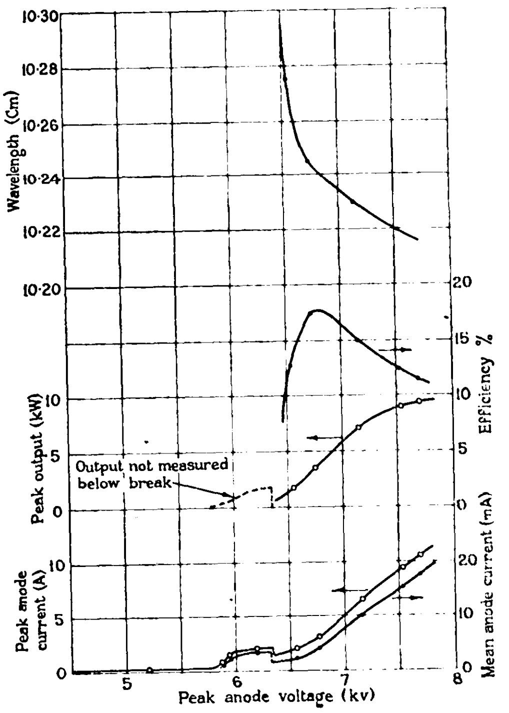

Fig. 12.—Performance figures for valve type E1189 No. 13 with water load.

$H = 1\ 000$ oersteds.
$E_f = 7 \cdot 5$ V.
Pulse 30 microsec, 50 pulses/sec.

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* See Fisk, J. B., Hagstrum, H. D., and Hartman, L. P.: *Bell System Technical Journal*, 1946, 25, p. 167; particularly Fig. 45.

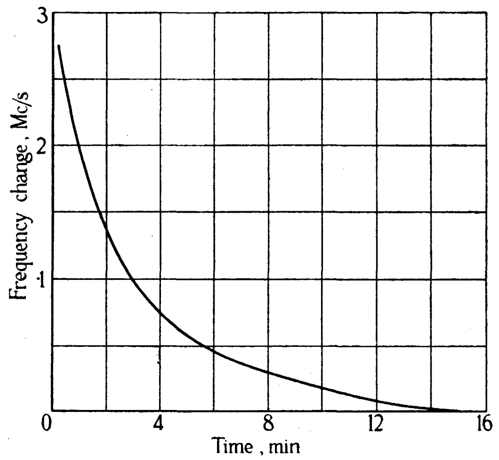

Fig. 13.—Frequency variation with time after switching on, E1198, No. 21.

Heater on 1 min before applying h.t.
Final temp. of outside of anode block about 60° C.
Peak E_a = 8 kV. Peak I_a = 8 A.
Mean I_a = 11 mA. H = 1 000 oersteds.

(4) TREND OF FURTHER DEVELOPMENT

While these first types were being established in pre-production intensive study of the possibilities of higher powers and shorter wavelengths went on, both on paper and in the laboratory. A 100-kW, 10-cm design was completed in September 1940 and gave the expected performance as soon as a suitable modulator was available. The process of reducing the wavelength without changing the size of the valve or magnet, by increasing the number of segments, was at first successful but soon encountered fundamental difficulties. This process was carried as far as a 60-segment design with wave-guide output for a wavelength below 1 cm; this was a mechanical *tour de force*, but it did not work!

The extension to higher powers was considered in some detail from the point of view of power/weight economy, scaling factors, and possible ultimate physical limits (power dissipation, cathode current-density, voltage gradient, and mass correction for velocity). These generalizations were all based on the assumption of an optimum value of H/H_c near 1·2, but they retained some value even after it was realized that this assumption was wrong and that the supposedly distinct "tangential resonance" oscillations were only a special case of the precessional resonance oscillations. It was the most serious practical problem of all, that of mode changing which is discussed in detail in the accompanying paper, which made it take so long to realize that with the new magnetrons as with the old the basic requirement for more efficiency in a given valve is more magnetic field.

At this stage the unusual requirements of magnetron cathodes were already appreciated, including the significance of cathode bombardment as one of the limiting factors which must be anticipated in future designs. As a preliminary to more intensive study of cathode problems an attempt was made to estimate the relative importance of thermionic and secondary emission. With the basic requirement that it must be possible for the anode current to build up to the operating value in a time small compared with the pulse length, it was concluded that the controlling factor is the product of the secondary-emission coefficient and the fraction of the outgoing electrons returned to the cathode. If this product exceeds a critical value in the neighbourhood of unity the thermionic emission can be a very small fraction of the required anode current, as found with the oxide cathode; if not, a thermionic emission comparable with the peak anode current must be provided. A rough estimate gave a value of the order of 3 for the minimum secondary-emission coefficient for a satisfactory magnetron cathode, and the observed behaviour of thoriated-tungsten and oxide cathodes (with secondary emission coefficients of about 2 and 6 respectively) was consistent with this conclusion.

(5) ACKNOWLEDGMENTS

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