Emilio Ciardiello

The development of the British cavity magnetron and the role of E.C.S. Megaw at GEC

The article, which presented the deductions following the accidental discovery in 2017 of the first laboratory prototype of the GEC E1189 8-cavity magnetron, was presented at the ninth conference of the AISI, the Italian Association for the History of Engineering, in 2022. It highlighted the role of the GEC Research Centre at Wembley and the essential role of E.C.S. Megaw in defining the cavity magnetron design, which would readily make the construction of microwave radar possible. The details visible in this prototype, such as the lateral peephole to measure the cathode's surface temperature, made us understand Megaw's meticulous attention to every aspect of the project. At the same time, we admired the masterful and fast synthesis he achieved in the summer of 1940 between the solution proposed by Randall and Boot, the advanced technologies then available at Wembley, and the parallel work carried out until then in Paris by Gutton and Berline.

In February 2024, into a lot of vacuum tubes from some old GEC warehouse, we found a magnetron, very different in design from the British ones. It turned out to be of French origin, an experimental 12-segment CSF M-16. It could only have been one of the two experimental prototypes promised by Henri Gutton to Megaw during the meeting in Paris in July 1939. This sample, resulting from some brainstorming between Megaw, Berline and Gutton in Paris in July 1939, has a tremendous historical relevance in the development of the British cavity magnetron, providing, together with the E1189 prototype, an exceptional withness to what Megaw wrote in his 1946 paper and, many years later, to the reconstruction from Yves Blanchard and others on the influence of French developments on the British design.

Below we give a selection of documents which, taken together, provide the history of the development of the British cavity magnetron.

A) ‘The development of the British cavity magnetron and the role of E.C.S. Megaw at GEC’, Emilio Ciardiello, IX AISI Conference, 2023
B) ‘The high-power pulsed magnetron: a review of early developments’, E.C.S. Megaw, 1946
C) ‘Microwave magnertrons: a brief history of research and development’, W.E. Willshaw, GEC Journal of Research No.2, 1985
D) ‘GEC’s wartime contribution’, W.E. Willshaw, CAVMAG 2010, Bournemouth
E) ‘The cavity magnetron: not just a British invention’, Yves Blanchard, Gaspare Galati, Piet van Genderen, IEEE Antennaa and Propagation Magazine, Vol 55, October 2013
F) ‘E1189 Prototype’, ase-museoedelpro collection
G) ‘M-16 CSF Experimental Magnetron’, ase-museoedelpro collection

October 2025

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Lo sviluppo del magnetron inglese a cavità ed il ruolo di E.C.S. Megaw alla GEC

Abstract
The cavity magnetron was essential to build microwave radar sets during WWII. Historical sources agree attributing its conception to Randall and Boot at the Birmingham University. Unfortunately, none worried to explain the substantial differences between the Birmingham prototype, a six-cavity CW device, and the pulse eight-cavity E1189 brought to America by the Tizard Mission. The recent acquisition to the ase-museoedelpro collection of the very early eight-cavity prototype, used by E.C.S. Megaw for test purposes at the GEC Research Laboratories in Wembley, made it possible to reconstruct the entire development of the British magnetron and the primary role he played. In a few weeks he managed to find in his E1189 magnetron the perfect synthesis between the structure devised by Randall and Boot and the most advanced solutions then available in England and worldwide.

Sommario
Il magnetron a cavità fu essenziale per costruire radar a microonde durante la seconda guerra mondiale. Le fonti storiche concordano nell'attribuirne la paternità a Randall e Boot dell'Università di Birmingham. Sfortunatamente, nessuno ha mai spiegato le differenze sostanziali tra il prototipo di Birmingham, un dispositivo CW a sei cavità, e l'E1189 a otto cavità per funzionamento ad impulsi, portato in America dalla missione Tizard. La recente acquisizione nella collezione ase-museoedelpro del primo prototipo a otto cavità, usato da E.C.S. Megaw a scopo di test presso i Laboratori di Ricerca GEC di Wembley, ha permesso di ricostruire l'intero sviluppo del magnetron a cavità e il ruolo primario da lui svolto. In breve tempo egli riuscì a trovare nel suo magnetron E1189 la perfetta sintesi tra la struttura proposta da Randall e Boot e le soluzioni più avanzate disponibili allora in Inghilterra e nel mondo intero.

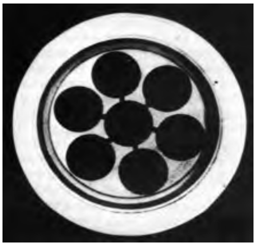
The history so far accredited

Historical sources agree on attributing the cavity magnetron to Randall and Boot, two researchers at the University of Birmingham. A team led by Professor Oliphant, for the transmitter of a 10 cm radar or RDF system, was working on a power klystron, the new vacuum tube devised at the Stanford University by the Varian brothers and based upon the cavity resonators theorized by Hansen. Due to the difficulties in obtaining linear electron beams dense enough to handle the required power, the two researchers were asked to integrate cavity resonators into a different structure [1]. The prototype conceived by Randall and Boot was not new for using cavities [2], rather because the resonator copper block was at the same time the outer envelope, dramatically improving heat transfer to the outside. It started to oscillate on February 21, 1940, generating bursts of 400 W at 9.8 cm, about ten times the power then obtainable with Oliphant's klystrons. It was a water-cooled six-cavity magnetron, wax-sealed and operated in the field generated by a big 5-inch gap electromagnet. On April 10, Eric Megaw from General Electric Company-GEC met Randall and Boot and proposed some solutions for sealing the device with thin end caps, so as to operate in a shorter air gap. On May 1st Randall, delegated by Oliphant, commissioned the GEC Research Center to build three evacuated prototypes: the subsequent GEC E1188 design led to the delivery of the three samples on May 16, 1940. The resonators had been provided by Birmingham and the tubes, which had no further follow-up, could operate into an air gap of "only" 7 cm. So far the stories told by Callick (Callick, 1990), Megaw [3], the same Randall [4] and others [1, 2, 5].

We know that the magnetron brought to America by the Tizard Mission, the GEC E1189 No. 12, differed remarkably from the E1188. Until today it was seen as an evolution of the Birmingham prototype, if not the result of lucky coincidences during empirical experiments made by Megaw on his own initiative. Such reconstructions contrast with the information given by Callick, that the first samples of E1189 were tested on the bench as early as June 29, 1940, even on June 28 according to Paterson (Clayton and Algar, 1991), while the E1188 prototypes were tested only in July. The chronological succession excludes evolutionary theses: Birmingham would never have deliberated on variations before testing samples made to its own design. Table 1 synthesizes the comparison between the Birmingham and the Megaw's magnetrons.

We know that the six-cavity prototype E1189 No. 1 had a thoriated tungsten filament, while the No. 2 had an oxide-coated cathode. All reconstructions then jump to the eight-cavity No. 12, the one brought to America by Bowen (Phelps, 2010). Nobody wonders when and where that variant came out and how many units were assembled. Stories of its appearance usually refer to the narration of the Tizard Mission left by Edward G. Bowen, who was directly involved in the development of airborne radar (Bowen, 1987). In his book he exposes in a smooth and elegant way what happened on 7 October 1940 when the E1189, which he himself had picked up two months before at GEC from a small lot of previously tested samples, was

Tab. 1 – Comparison between the Birmingham and the Megaw's magnetrons.

GEC code	*E1188 (Birmingham, sealed)*	*E1189, revision C (Megaw)*
Type	Continuous wave, 9,8 cm	Pulse, 9,8 cm
Anode	Six-cavity, Randall's design	Eight-cavity, Megaw's design
Magnet gap	70 mm	37,5 mm
Cooling	Water	Air
Cathode	Filamentary, tungsten	Oxide, indirect heating
Out power	400 W CW at 1.000 Oersted	15 kW pulses at 1.050 Oersted
Samples	May 16, 1940, tested in July	28 or 29 June 1940
Resonating system [4, 6]		

x-rayed at Bell unveiling its eight-cavity internal structure. The accident aroused astonishment and suspicions, since documentation and drawings all referred to a six-cavity device. Bowen tells of his phone call to Megaw in England and of the confused reactions to the other end of the phone. He adds details about quantities and structures of the GEC prototypes, which were repeated by subsequent authors. But his book was written half a century after facts covered by utmost secrecy. Parts of his tale probably came from faded memories of people just hearing about the magnetron at GEC. The image one gets from reading is that no one knew how that experimental prototype ended up in America and that Bell finally decided to make copies of it only due to the lucky circumstance of having seen that sample working fine on the bench. The confusion picture that emerges from Bowen's memories was viewed by some as a proof that his reconstruction was accurate. In fact, the dramatic Battle of Britain took place in the summer of 1940, with a frantic English race for deploying any kind of resources and countermeasures, even if still experimental and untested.

We will remember here that Eric Megaw was designing high frequency vacuum tubes at the GEC, Hirst Research Center in Wembley, since the early thirties. In 1933 he published an article on magnetrons in the Journal of the Institution of Electrical Engineers. In 1935 he collaborated with Philips' Posthumus in a letter to Nature on extending the rotating cloud theory to the split-anode magnetron. He designed commercial and experimental magnetrons: in Fig. 1A we see a CW10, released in 1936,

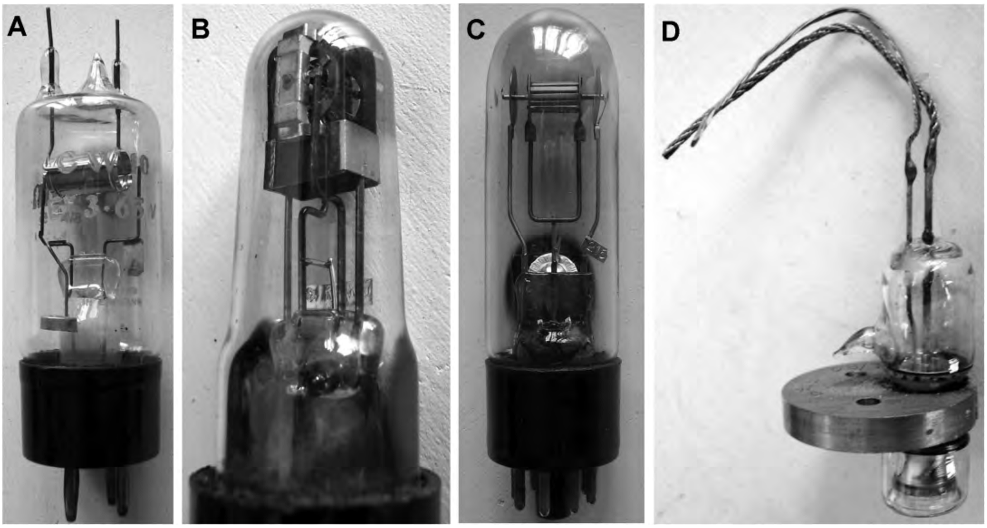


Fig. 1 – Megaw's early magnetrons: the CW10 split-anode (A), samples of eight and twelve-segment squirrel-cage magnetrons (B, C), UHF milli-micropup triode (D).

and in Figs. 1B and 1C two "squirrel cage" interdigital prototypes, one with eight and one with twelve segments [7]. Megaw investigated the back-bombardment phenomenon, explaining how the resulting emission could keep the tube oscillating, reducing or even removing the filament power supply. In 1937, for an Admiralty communications system, Megaw developed the E880 four-segment magnetron, with thoriated-tungsten filament [5]. We also know that he was personal friend of Henri Gutton of the SFR. In June 1939 in Paris they discussed the new SFR M16 magnetron, with oxide cathode. In May 1940 Maurice Ponte brought to him two M16 samples and their behavior on the test bench influenced the design of the second E1189 prototype, modified to accommodate the high emission oxide cathode (Callick, 1990) [2].

In December 1939, while Randall and Boot were designing their magnetron, GEC was developing for the Air Ministry an AI prototype operating at 25 cm, based upon still experimental milli-micropup triodes, as the one of Fig. 1D. By March 1940 the specification had been uprated to 10 cm. Megaw was therefore designing a four-segment magnetron with thoriated-tungsten emitter, when he was asked to examine the prototype of his former colleague Randall [1].

The very early prototype of the GEC eight-cavity E1189, revision C

Our prototype, visible in Fig. 2, is today preserved in the ase-museoedelpro collection. It was accidentally found in England in 2017, in a huge lot of historic tubes, probably the same on display at the M90 Historic Microwave Exhibition held in

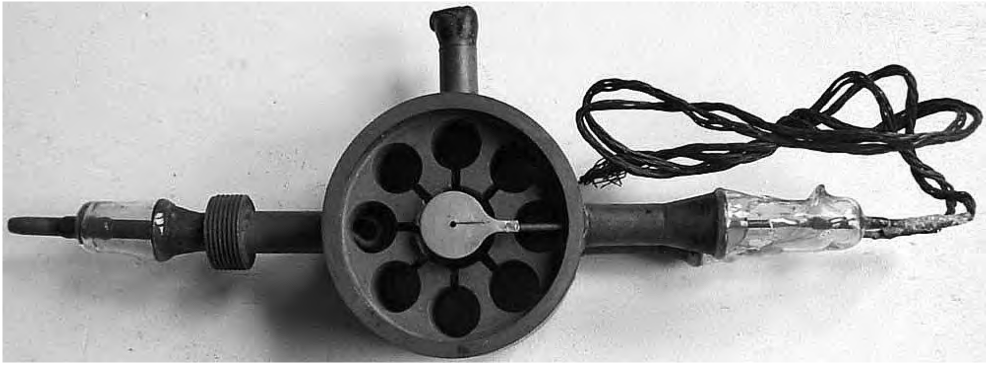


Fig. 2 – The very early laboratory prototype of the eight-cavity GEC 1189 C 328 [6].

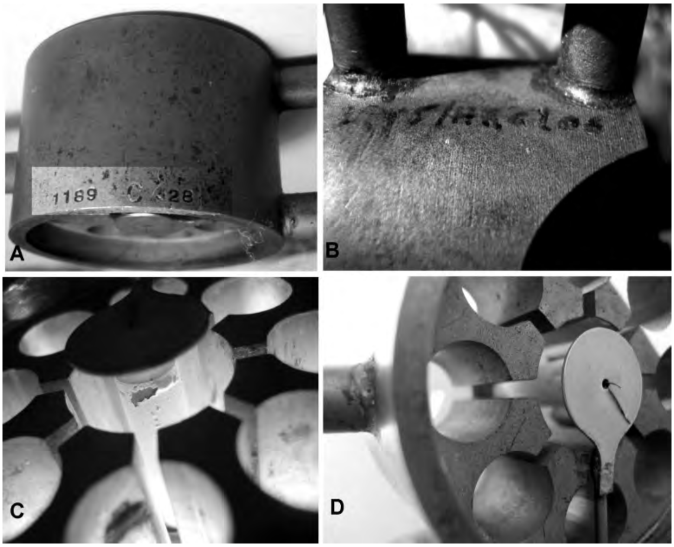
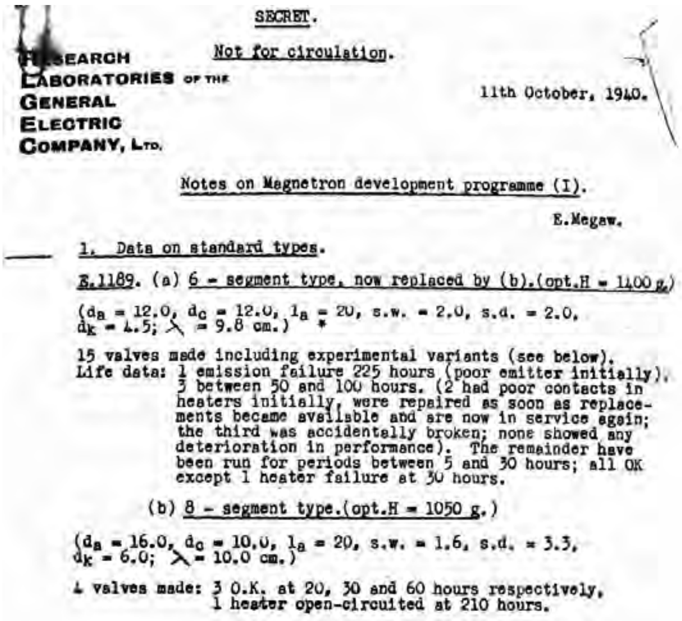


Fig. 3 – Close-up views of the sample: the code 1189 C 328 is punched on the external wall (A), characters HR210 are in the felt-tip writing (B), the partially detached oxide layer denotes heavy overloads or arcing (C) and heater wire broken close to the welding to the end baffle: the oxide layer is very thin, so to expose the bare nickel surface (D).

London from 11 to 13 July 1990 and later at the M94 and at the M96 exhibitions (M90, M94 and M96 Catalogs). It was believed to be just one of many magnetrons dissected to show their internal geometry. Anyway, very singular details began to appear upon closer inspection. The code “1189 C 328” was punched close to the edge of the external wall, Fig. 3A. Characters “HR210” could be read in the felt-tip writing of Fig. 3B. Fig. 3C shows the partially detached cathode oxide layer, as resulting from heavy overloads or arcing. In Fig. 3D we see the heater wire broken close to its welding to the cathode end baffle. The oxide layer nearby looks very thin, so to expose the bare nickel surface for a considerable area. Except for the absence of the finned radiator and for the presence of the lateral copper tube, its shape resembled that of the GEC E1189 given by Callick. Traces of grease into the inner edges suggested that the tube had been operated with removable caps, while continuously connected to the vacuum pump. The presence of the small copper tube, pointing upwards in Fig. 2, was definitely unusual. The short tube recalled the peephole encountered in literature to measure the cathode temperature of experimental power magnetrons, such as the LCW type described by Collins (Collins, 1947). Back-bombardment phenomena raise the cathode temperature, hence their effect must be monitored and counteracted, reducing or even removing the filament voltage.

Many signs indicated that the prototype had been used in the laboratory for severe tests, until the heater failure. To find out more, we started examining carefully the available documents of the time. Very relevant was the GEC internal report of Fig. 4, a six-page document on the early cavity magnetrons left by Megaw himself [8]. This report is extremely interesting because it also lists the many experimental


SECRET.

Not for circulation.

RESEARCH LABORATORIES OF THE GENERAL ELECTRIC COMPANY, LTD.

11th October, 1940.

Notes on Magnetron development programme (I).

E.Megaw.

1. Data on standard types.

E.1189. (a) 6 - segment type, now replaced by (b).(opt.H = 1400 g.)

(d_a = 12.0, d_c = 12.0, l_a = 20, s.w. = 2.0, s.d. = 2.0, d_k = 4.5; λ = 9.8 cm.) *

15 valves made including experimental variants (see below).
Life data: 1 emission failure 225 hours (poor emitter initially). 3 between 50 and 100 hours. (2 had poor contacts in heaters initially, were repaired as soon as replacements became available and are now in service again; the third was accidentally broken; none showed any deterioration in performance). The remainder have been run for periods between 5 and 30 hours; all OK except 1 heater failure at 30 hours.

(b) 8 - segment type.(opt.H = 1050 g.)

(d_a = 16.0, d_c = 10.0, l_a = 20, s.w. = 1.6, s.d. = 3.3, d_k = 6.0; λ = 10.0 cm.)

4 valves made: 3 O.K. at 20, 30 and 60 hours respectively, 1 heater open-circuited at 210 hours.

Fig. 4 – Extract of the Megaw’s internal report on magnetron valves [9].

types he made in a couple of months, from the release of the eight-segment E1189 in August to the first ten days of October. Among the many types listed, we read of four E1189 eight-segment units, "opt. H = 1050 g". One of them had just operated 210 hours, before opening of the heater. The document seems to contradict another paper written by Megaw in 1946, which only mentions two eight-cavity units, the No. 12 and the No. 13 [3]. The inconsistency could be explained, assuming that the second paper listed only the tubes completed with radiator, sealed and serialized. As said before, our prototype is incomplete. It was only partially assembled to operate in the laboratory while connected to the vacuum pump.

The diary of Sir Clifford Paterson (Clayton and Algar, 1991), at the time director of the Wembley Research Center, briefly provides us with facts and dates relating to the development of the magnetron at GEC and to its eight-cavity variant. Here we read that «Megaw thinks well » of the Randall magnetron. We learn of the two Megaw's designs, the "air-cooled" and the "air-cooled low-field" ones[1], in comparison with the Randall's one. We also read that Randall, with the assistance of the technologist Duke, who had been moved from GEC to Birmingham, had worked before August 6 to a 5-cm scaled-down copy of the Megaw's air-cooled type. The main events noted are summarized in Fig. 5.

The chronology left by Paterson, along with what Megaw and others wrote, helps us to date the key steps of the E1189 development in the Table 2.

The emerging picture shows the Megaw's fundamental role in designing the cavity magnetron, the basic component of the microwave radar. Randall certainly devised a brilliant solution for a powerful generator, but his device was similar in performance to other contemporary types, even outclassed by the SFR M16. Possibly it would have just remained a laboratory curiosity without Megaw's contribution. In fact the now useless E1188 samples will be tested only in July, perhaps to formally close the

May 1st[86]

Randall from Birmingham came instead of Oliphant to get us to start quickly with replicas of three large magnetrons which Megaw thinks well of. Had to speak straight to Randall for Oliphant is an impatient person and expects first priority which we could not give him. I think Birmingham must have the main responsibility for the tubes or they will never be happy.

June 28th[104-105]

Randall coming on Friday re. high power magnetron. Megaw and Boyland have been making splendid progress with these. There are two types—Randall's and Megaw's—the former water-cooled and the latter air-cooled. At the moment Megaw's is on circuit and giving some 2 kW at the desired wavelength—but Randall's will follow in the next few days. Boyland's gold wire joint seems to be one of the chief features giving the striking success.

July 1st

Output from Megaw's 10 cm magnetron has risen to 4 or 5 kw and is still rising.

July 17th

The whole day at our two-monthly CVD meeting. A rather memorable occasion for we recorded (*a*) beam valve amplification at 50 cm, (*b*) Megaw's air-cooled low field magnetron, (*c*) Ramsay's mercury modulator, (*d*) two velocity modulation receiving tubes—one with resonator for 10 cm. General demand for specimens.

August 6th[113-114]

A crowd of people here from many establishments including Oliphant and Randall and Ellis. It is difficult for people to get on with urgent work when visitors are so frequent but it cannot be helped. Megaw's improved 10 cm magnetron with eight chambers appears up to expectations. Randall with Duke's assistance (we introduced him to Oliphant) has made a good copy of the air-cooled magnetron for 5 cm.

August 7th[115]

Schoenberg, Blumlein, Condliffe and Broadway with Bowen came for a thorough discussion of AI. It took a whole morning and until 3 o'clock. The general exchange of views and experience was helpful and the atmosphere of co-operation most encouraging.

Fig. 5 – From the diary of Sir Clifford Paterson (Clayton and Algar, 1991).

Tab. 2 – Development steps of the E1189 magnetron.

10 April	Megaw is shown the Randall and Boot's prototype.
1 May	The E1188 project starts, with resonators supplied by Birmingham. Soon later the E1189 low-profile project by Megaw takes off.
9 May	Maurice Ponte of SFR brings two M16 samples to Megaw. After a performance check, Megaw designs a second E1189 with oxide-coated cathode.
28 or 29 June	The two six-cavity E1189s start to operate, generating 1 kW pulses. In a few days the peak output power of the No. 2 rises to over 10 kW.
8 July	The Tizard Mission is officially underway (Phelps, 2010). Perhaps at that date Megaw was already considering an eight-cavity variant, to increase efficiency in the low magnetic field of a 6 lbs permanent magnet.
17 July	At GEC the CVD committee discusses « the low-field Megaw magnetron». Samples of six and, whenever ready, of eight-cavity are then requested.
30 July	Probably at this date the first eight-cavity E1189 - our sample - starts oscillating, continuously connected to the vacuum pump.
1 August	In accordance with the worked hours, the second prototype starts oscillating.
4 - 5 August	The two finished E1189s, No. 12 and 13, start running on the bench.
6 August	Paterson writes: «The Megaw's improved 10 cm magnetron with eight chambers appears up to expectations». It is the approval of the new eight-cavity design by that crowd of officials, including Oliphant, Ellis and Randall. The first prototype will continue stress and endurance tests until its heater opens.
7 August	Bowen and the key people involved in the 10cm AI radar discuss the details. At the end Bowen, chosen for the Tizard Mission, will select the best performing sample from the batch of E1189 previously tested by Megaw: it is the eight-cavity No. 12. The magnetron and the folder with the production documents of the six-cavity, the one approved until the day before, will be kept in the safe at the GEC until August 11, when Bowen is back to Wembley to pick them up (Bowen, 1987)
6 October	The E1189 No. 12 is powered at the Bell Laboratories in Whippany, generating 15 kW pulses in a field of 1100 gauss. The sample and drawings of the six-cavity type are left at Bell, who is asked for a small lot of evaluation and qualification copies (Bowen, 1987; Conant, 2002; Phelps, 2010)
7-8 October	X-ray of magnetron No. 12 unveils its eight-cavity structure. Bowen is recalled to Whippany. He phones Megaw, who appears puzzled: but that project had ended two months before and the perplexity felt by Bowen at the other end of the phone seems quite justifiable!

order. The E1189 project, entirely attributed to Megaw by Paterson, best integrated Randall's solution with the emission capacity of the oxide cathode tested by Gutton. The result was then perfected, recalculating in a very short time the geometries for eight-cavity, to increase its efficiency in the reduced field of a permanent magnet. Contrary to what is commonly believed, after the Megaw's visit to Birmingham and the subsequent move to that site of the technologist Duke, the transfer of know-how was activated in the opposite direction, from GEC to Randall, allowing him to readily prepare a 5-cm copy of the Megaw's E1189 (Clayton and Algar, 1991). It is evident that the eight-cavity low-field variant was authorized during the CVD meeting on 17 July. Its whole project was therefore carried out in a couple of weeks, relying upon the already tested six-cavity if it failed. Our sample proves how carefully the steps necessary to its characterization were planned. Then we understand the full meaning of the words written by Megaw in 1946 and the presence in our sample of the lateral copper tube, certainly what remains of a peephole to measure the cathode temperature with a pyrometer. In his 1946 paper [3] he pointed out how he had roughly estimated its value on the second six-cavity sample, by measuring the resistance of the heater: «The output at 6 microsec was independent of heater voltage down to zero with oxide-cathode sample [...] 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».

We know that this was a totally new geometry, never experienced before and, even worse, with indirectly heated cathode. Megaw had to specify the proper heater voltage for typical operating conditions. Certainly it could not be set to any tentative value «down to zero». The cathode temperature could only be measured by pyrometric methods and, being the copper wall entirely opaque, he had to place that peephole to characterize his tube.

In our reconstruction there were still doubts about the fourth prototype listed by Megaw. Eventually this too was found. The image in Fig. 6 shows the second 1189 C328 laboratory prototype, absolutely identical to our sample. It comes from the page of an old GEC website, which highlighted the products introduced in about one hundred years of activity. Then we have the two laboratory prototypes plus the two samples listed in the 1946 Megaw's paper [3], complete with radiator and caps and serialized as No. 12 and No. 13. According to Trevor Wright, who hosts the old GEC website, the second sample was preserved in the collection of the Marconi Research Center in Chelmsford, today dispersed after the shutdown of GEC first and of British Marconi few years later.

The fundamental role of Megaw in the development of the cavity magnetron is then evident. The story that emerges, even if less romantic than the one left by Bowen, shows him as the leading and most experienced figure on magnetrons who, even thanks to the unlimited support of GEC, will transform the Randall and Boot's successful experiment into a readily usable microwave generator, soon reproduced in hundreds of thousands copies and variants. It should be added that the E1189 No. 12, although made in great haste, was the result of careful planning and in-depth testing, when it began its journey to America in the Bowen's luggage.

Fig. 6 – Cut-out of the page from the GEC site on the second 1189 C328 prototype [7].

Most likely the accompanying papers had been prepared in advance with drawings of the six-cavity E1189, the only one approved until the evening of August 6. When the next day Bowen picked up the No. 12, the blueprints locked into a safe were not updated. Understandable oversight at the end of that August 6 described by Paterson!

Subsequent developments of E1189 during the war

For evaluation purpose, from November 1940 Bell hastily built a few copies with its developmental code 1259M, largely for the National Defense Research Committee-NDRC and other research laboratories. A sample is preserved today in the collection at University of Birmingham: due to haste, one of the code digits was printed upside down. About sixty more copies were built in 1941 under the code D-160052 by the subsidiary Western Electric, which also put into production in the same year its 25 kW peak ruggedized variants, the 706A to 706C of Fig. 7D [8, 10].

The units manufactured in England from 1941 came out with four-fin radiator. Type E1189 was approved by British Admiralty as NT98, Admiralty Pattern W2510 of Fig. 7A. In Canada the same tube was produced by the Bell related Northern Electric, as REL Type 3D, Fig. 7B. It was used in the RX/C naval systems and in the GL3C wheeled trailer (Knowles Middleton, 1981). There was also an Australian production, as NTA98, by Australian Standard Telephones and Cables, also related to Bell. The 9.1 cm variant for the Air Ministry, the E1198, was approved as CV38. It was also built in Canada as REL 3C, Fig. 7C.

No need to list the countless types of cavity magnetron directly derived from the Megaw's E1189 design and made through the war in America and England, and

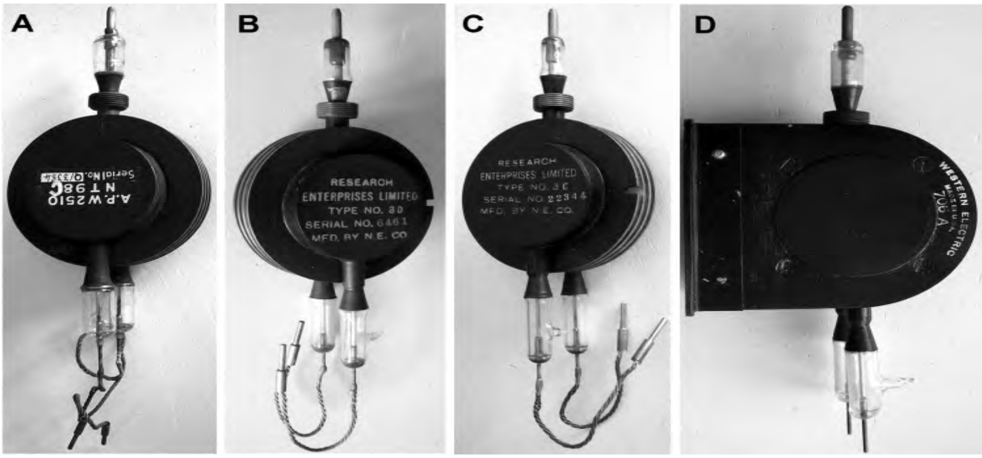


Fig. 7 – The E1189, approved by the Admiralty as NT98 (A); the same type made in Canada as REL 3D (B); the Air Ministry variant CV38, here as REL 3C (C); Western Electric heavy duty version 706A to D (D) [8, 10].

since 1944 also in Germany. Geometries were readily recalculated to operate at fixed frequencies between 700 MHz and 24 GHz, Also tunable types appeared, to reduce the inventory of spare parts. The “strapping techniques”, first devised in July 1941 at Birmingham by Sayers, greatly reduced the intrinsic trend to “mode jumping” during transients, so making it possible to increase the efficiency and in any case to attain peak power pulses in the order of megawatts. “Packaged” magnetrons were introduced, with factory-installed magnet, to facilitate their in-field replacement.

The same production processes were enormously perfected. The most impressive improvement involved the manufacturing of the resonator block, which also works as anode and as outer envelope. Cavity magnetrons required slow processing of the heavy anode copper block to drill the cavities, end caps being sealed with gold wires. Early in 1941 Western Electric had opened in Chicago a special facility, financed by the Navy and equipped with long lines of drilling stations. Soon later Percy Spencer at Raytheon succeeded in growing anode blocks from thin metal sheets, by stacking copper discs machine-punched to the proper shape and then silver-brazing them into hydrogen ovens. As a result, Raytheon was able to build 2,400 magnetrons per day (Scott, 1974), compared to the approximately 2,000 units of E1189 manufactured by both BTH and GEC in 1941. Tizard’s most optimistic predictions were far exceeded.

The ase-museoeselpro collection has on display about 120 magnetron types: many of the pulse types retain the same overall shape and well illustrate the evolution of the first E1189 prototype designed by Megaw at GEC [8].

Acknowledgements
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Bibliography
Bowen E.G. 1987. *Radar Days*. London: Adam Hilger.
Callick E.B. 1990. *Metres to Microwave Metres to Microwaves: British Development of Active Components for Radar Systems 1937 to 1944*. London: Institution of Engineering and Technology.
Clayton R., Algar J. 1991. *A Scientist's War: the diary of Clifford Paterson*. London: The Institution of Engineering and Technology.
Conant J. 2002. *Tuxedo Park*. New York: Simon & Schuster.
Collins G.B. 1947. *Microwave Magnetrons*. New York: Mc Graw Hill.
Kingsley F.A. 1995. *The development of radar equipments for the Royal Navy, 1935-45*. London: Palgrave Macmillan.
Knowles Middleton W.E. 1981. *Radar development in Canada: The Radio Branch of the National Research Council of Canada 1939-1946*. Waterloo: Wilfrid Laurier University Press
M90, M94, M96 Historic Microwave Catalogs, self-published
Phelps S. 2011. *The Tizard Mission: the Top-secret Scientific Mission that Changed the Course of Wwii*. Yardley: Westholme Publishing.
Scott O.J. 1974. *The creative ordeal, the story of Raytheon*. New York: Atheneum.

Webgraphy
[1] Lazarus, 1986
http://www.ase-museoedelpro.org/Museo_Edelpro/links/P-06.pdf
[2] Blanchard et al., 2013
http://www.ase-museoedelpro.org/Museo_Edelpro/links/P-05.pdf
[3] Megaw, 1946
http://www.ase-museoedelpro.org/Museo_Edelpro/links/P-03.pdf
[4] Boot and Randall, 1946
http://www.ase-museoedelpro.org/Museo_Edelpro/links/P-01.pdf
[5] Willshaw, 1990
http://www.ase-museoedelpro.org/Museo_Edelpro/links/P-07.pdf
[6] E1189 Prototype
http://www.ase-museoedelpro.org/Museo_Edelpro/links/TM-01.pdf
[7] GEC site
http://www.trevorwright.com/GEC/Archive/magtron.html
[8] Magnetron page
http://www.ase-museoedelpro.org/Museo_Edelpro/links/TM-ix.pdf
[9] Megaw, 1940
http://www.ase-museoedelpro.org/Museo_Edelpro/links/P-02.pdf
[10] Fisk et al,, 1946
http://www.ase-museoedelpro.org/Museo_Edelpro/links/P-04.pdf

Index of abbreviations

AI: Air Intercept, an airborne radar set
BTH: British Thomson Houston Ltd.
CVD: (Ultra Short Wave) Communication Valve Development
CW: continuous wave
GEC: General Electric Company Ltd.
RDF: Radio Direction Finding, British equivalent for radar
SFR: Societe Francaise Radioelectrique, Paris

Note

1. Almost certainly Paterson used the definition “air-cooled” referring to the six-cavity E1189 prototypes, requiring 1500 gauss for 10 kW pulses, and “air-cooled low field” for the subsequent eight-cavity variant, capable of full operation at 1050 gauss.

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

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(*The paper was first received* 28*th January and in revised form* 25*th February*, 1946.)

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-

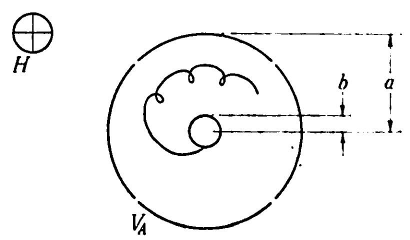


Fig. 1.—Illustrating precession of electron orbits in a cylindrical system.

* Radio Section paper.
† Admiralty Signal Establishment; formerly G.E.C. Research Laboratories, Wembley.

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

* See page 991.

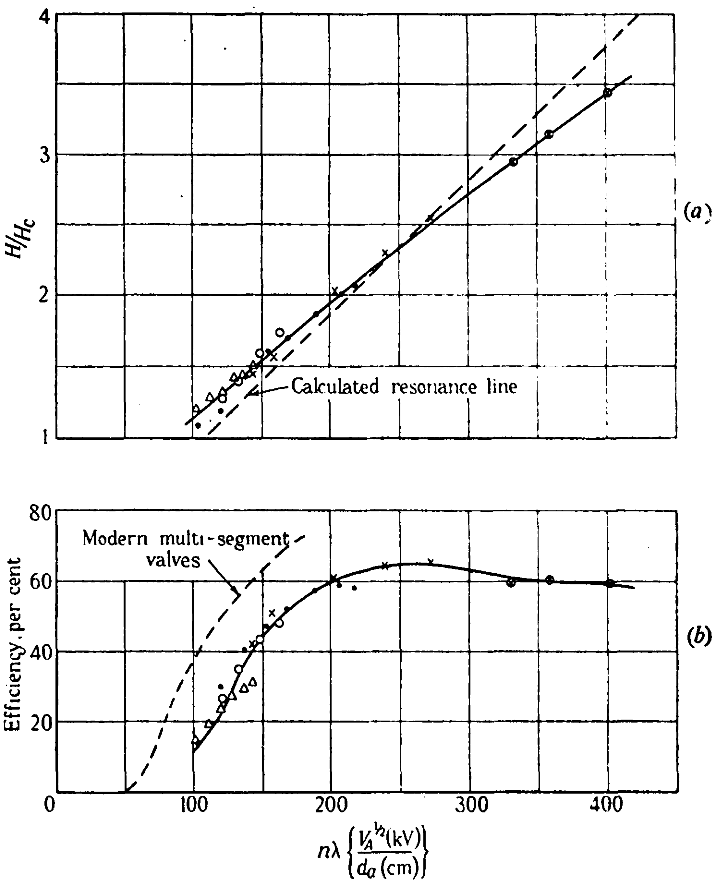


Fig. 2.—Generalized operating characteristics.

4-segment magnetron type E880 No. 631.
$n = 2$. $d_a = 2a = 0.7$ cm.
Cathode diameter $= 2b = 0.025$ 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 ⊗

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.

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.

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 $n\lambda H(1 - b^2/a^2) = \text{const.}$, 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

* 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

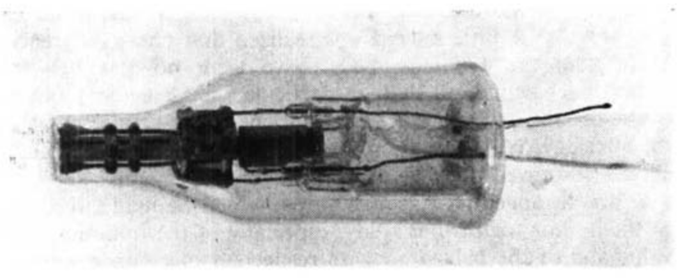


Fig. 3.—Low-power magnetron with integral anode and resonant circuit for about 3-cm wavelength.

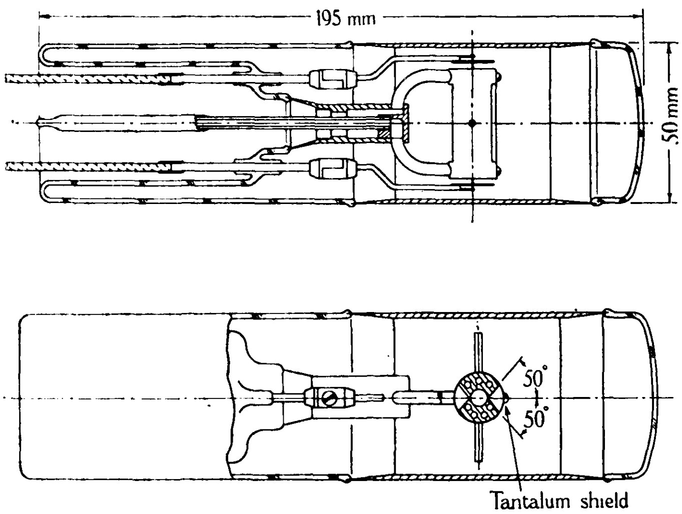


Fig. 4.—Water-cooled resonant-segment magnetron design for high-power c.w. operation at 5 cm wavelength (March 1940).

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.

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

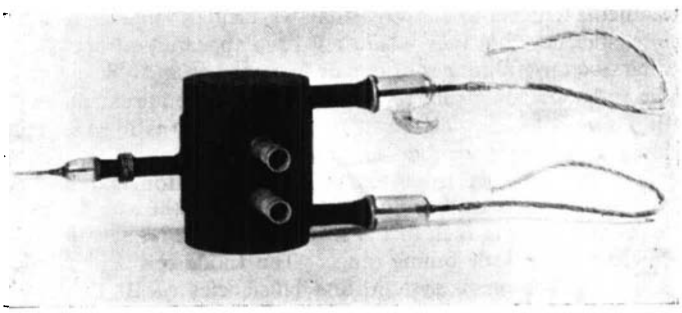


Fig. 5.—E1188, No. 1. Improved model of Randall–Boot tungsten-filament magnetron; designed and made in collaboration with Birmingham University. (Design completed 16th May, 1940.)
C.W. or pulse output of the order of $\frac{1}{2}$ kW at 10 cm. Electromagnet weight 50 lb.

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.

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

* 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

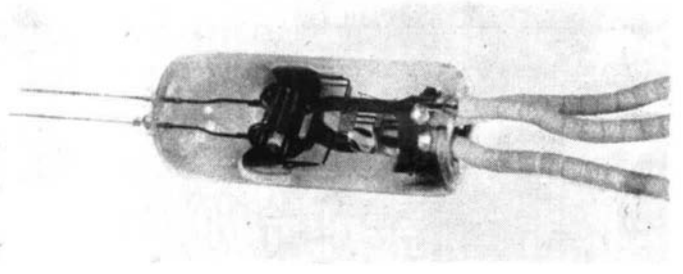


Fig. 6.—Gutton resonant-segment magnetron, type M16, with oxide cathode, for pulse or c.w. operation. (Sample received 8th May, 1940.)

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

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.

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 $1 \cdot 2\,H_c$ (the approximate operating conditions for the Birmingham valve gave about $1 \cdot 4\,H_c$); and no oscillations were obtained below cut-off field. Fig. 7 shows some of the results. The two ranges

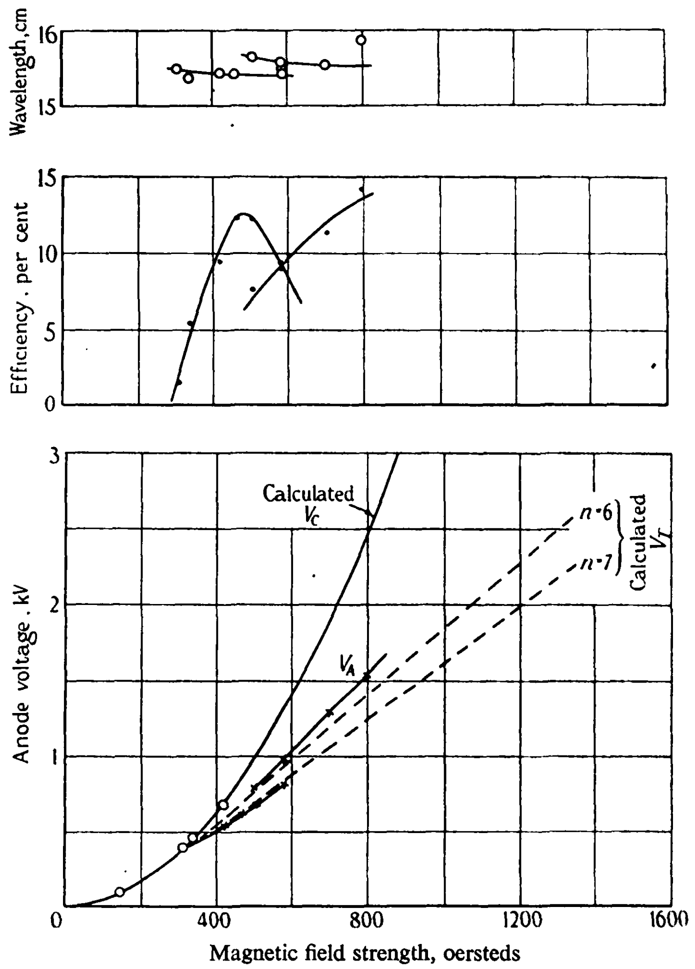


Fig. 7.—Operating characteristics of M16 magnetron.

$n = 6$. $a = 0 \cdot 5$ cm. $b = 0 \cdot 2$ cm.

V_A for maximum efficiency.

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.

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

* 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)

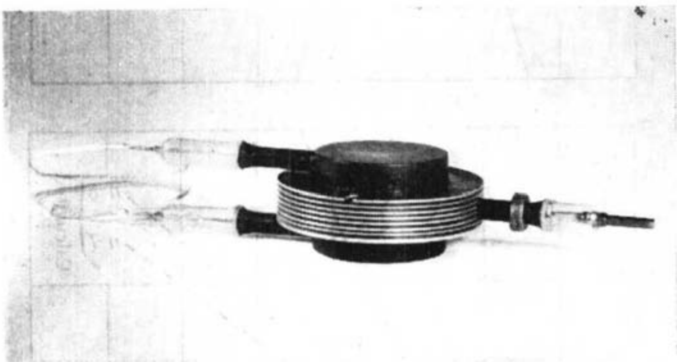


Fig. 8.—E1189, No. 1. Original design for high-power pulse operation in aircraft. (Design completed 25th May, 1940. First operated 29th June, 1940).

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.

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.

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.

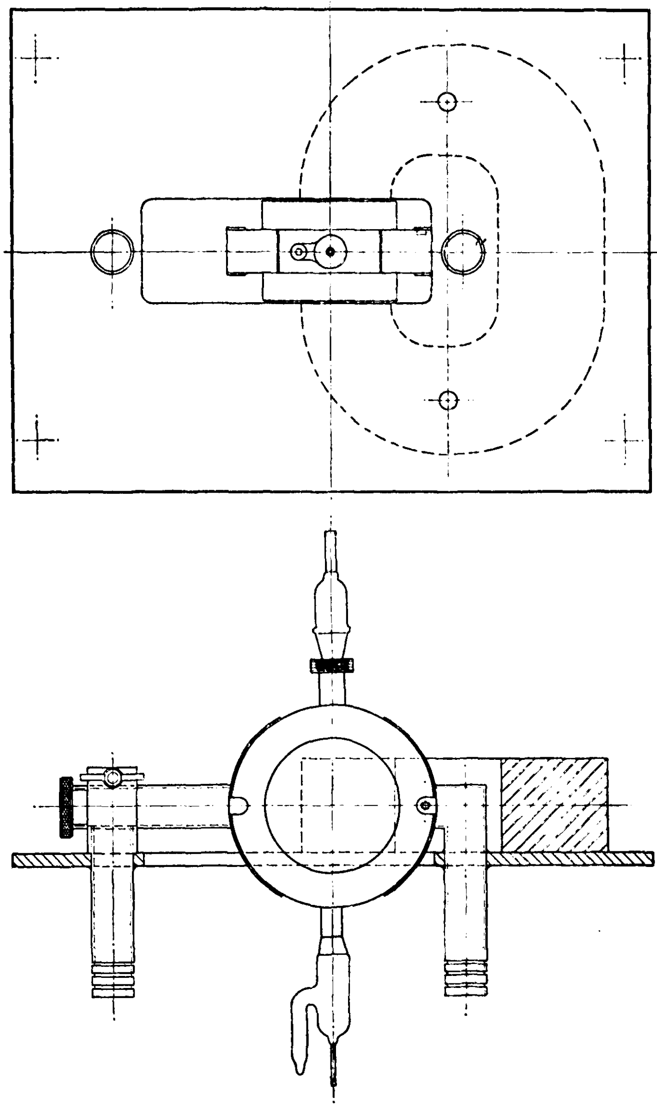


Fig. 9.—Original valve- and magnet-mounting for E1189.

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.

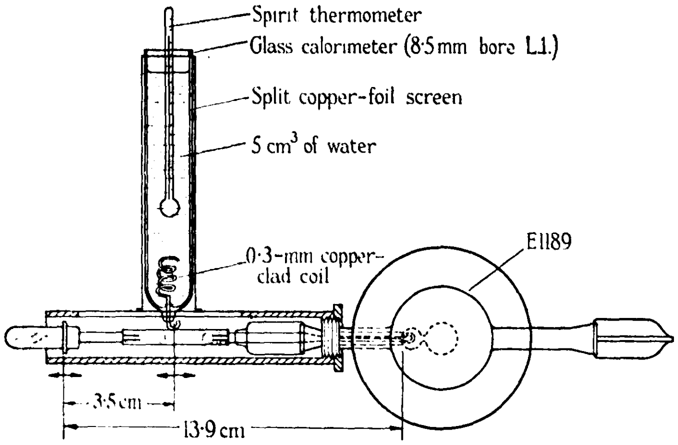


Fig. 10.—Original output circuit and water load for E1189.

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.

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

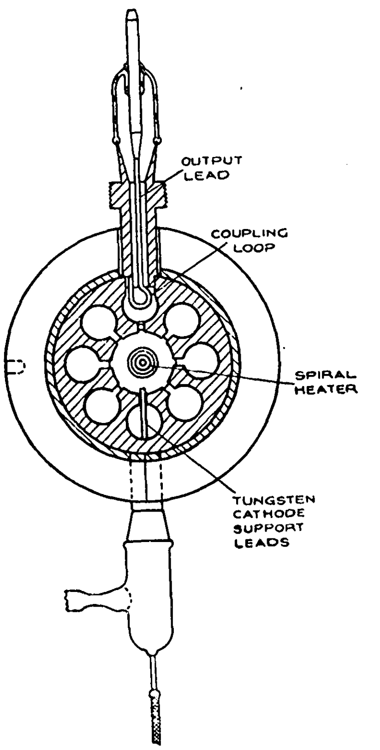


Fig. 11.—Internal construction of E1189 magnetron in final 8-segment form (from Serial No. 12).

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

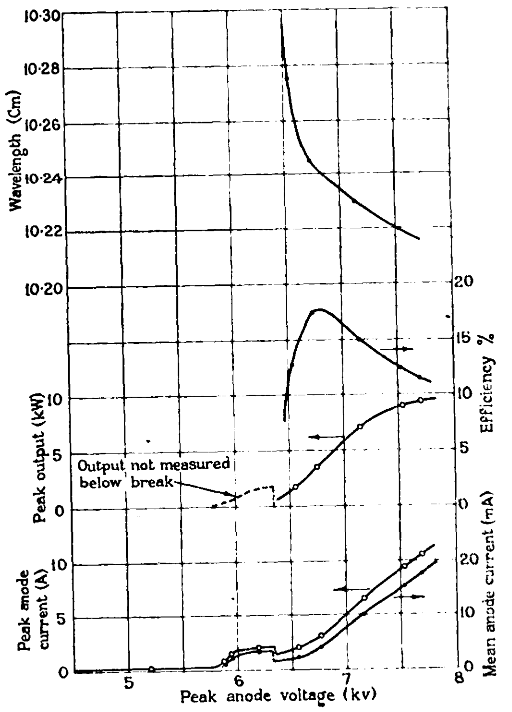


Fig. 12.—Performance figures for valve type E1189 No. 13 with water load.

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

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.

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

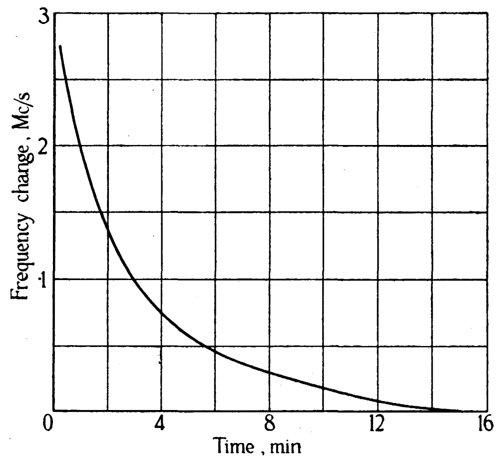


Fig. 13.—Frequency variation with time after switching on, E1198, No. 21.

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

The work described in this paper was carried out in the G.E.C. Research Laboratories as part of a research and development programme undertaken for the Admiralty. The author is indebted to the Department of Scientific Research and Experiment, Admiralty, for permission to publish the paper.

MICROWAVE MAGNETRONS: A BRIEF HISTORY OF RESEARCH AND DEVELOPMENT

W. E. WILLSHAW

In this history of the evolution of the magnetron, the essential steps in the transition from the first glass envelope magnetron device to the copper block design are briefly outlined. These are followed by short accounts of the main stages of elaboration which have led to present day magnetrons. In view of the vast range of application and the tremendous effort deployed on development during wartime and following years, attention has been concentrated on basic design steps and overall performance, with little attention to detailed performance.

EARLY STEPS

The present day magnetron is the result of extensive researches and developments under the stimulus of defence requirements. However, it originated from the research by Hull in the USA to resolve a patent dispute. In 1921 he invented the magnetron diode[(1)]. In this, an axial magnetic field provided the means to control the current passing through a smooth bore cylindrical coaxial diode by bending the electrons away from the anode, figure 1(a). It was developed as an audio amplifier and r.f. source but, following the resolution of the dispute, was no longer needed, and development ceased.

In 1928, Zacek showed that oscillations could be produced in the simple diode at the critical (cut-off) magnetic field with a frequency close to the cyclotron frequency[(2)], that is, the angular frequency of rotation of an electron around a magnetic field.

In 1924, Habann had described a split anode system producing negative resistance oscillations[(3)]. In this, variation of potential of either anode segment, with a magnetic field greater than the 'cut off' value, results in a greater current flowing to the lower potential segment than that to the higher potential segment, figure 1(b). Thus the magnetron behaves as a negative resistance to a circuit connected across the segments, and oscillations can be produced over a wide range of frequencies below those for which electron transit time is significant.

In 1929, Okabe published Japanese work using a split anode system to generate centimetre waves[(4)]. This attracted world wide interest in the practical possibilities of the magnetron and from 1933 onwards a steady stream of workers in Europe, Russia, Japan and America developed both practical and theoretical ideas on the use of the magnetron for short wave generation. Among these was Megaw of the GEC Research Laboratories at Wembley[(5)].

Use of multi gap anode

Comparison of performance obtained by different workers, who did not have the means of rapid contact enjoyed today, was made difficult by the various possible 'electronic' and 'circuit' modes of oscillation. However the successful development by Postumus in 1934 of a 4-segment magnetron, figure 1(c), and the rotating field theory by which he explained its advantage over a similar 2-segment system[(6)], was a major step forward which anticipated later theoretical work, and showed the advantage to be gained by the use of a multiplicity of anode segments in reducing the magnetic field at which a given efficiency could be obtained.

First use in system

As an example of the state of application of the 4-segment magnetron in 1937, figure 2, shows the valve developed at GEC, Wembley, for operation in the range 40–60 cm and used in the circuit shown schematically whilst figure 3 shows the complete transmitter of a communication equipment for use at sea, also developed at Wembley[(7)]. This was for studies of the problem of secure communication at centimetre wavelengths. In view of the need for frequency stability, the equipment was fitted with a coaxial resonator, by means of which the frequency was stabilized and could be switched as needed for operational reasons, and the anode voltage was stabilized. The power produced was 20 W at about 1000 V and modulation was by square wave switching of the anode voltage. Twelve sets of the equipment were made by GEC Telephone Works and most of these had been fitted on HM ships by the time World War 2 started.

This work was carried out, of course, with the closest possible cooperation of the Admiralty, and especially with officers of HM Signal School at Portsmouth. Together with other special work on valves for the Air Ministry, it led to the appointment of C. C. Paterson, Director of the GEC Research Laboratories, as Chairman of the Government Inter Services Valve Technical Committee (later CVD). This initiated the close relationship that has been maintained at the highest levels between the valve interests of the GEC and those of the Defence Services.

Large cathode

An important factor in the rapidly growing development of the magnetron was the diameter of the cathode which from the earliest days had been kept small (about 3% or less of the anode diameter). In 1939, in the course of discussions between Megaw

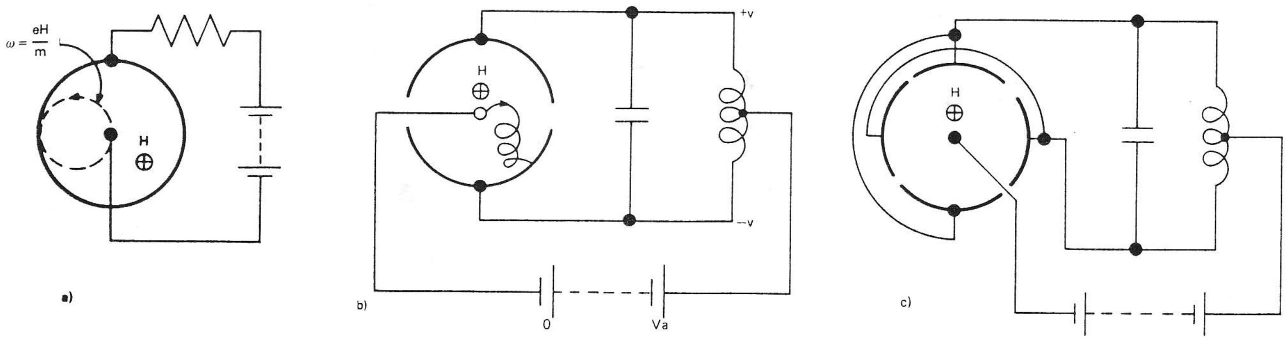


Fig. 1. Some early experimental magnetrons (a) Hull, 1921 and Zacek, 1928 (b) Habann, 1924 (c) Postumus, 1934

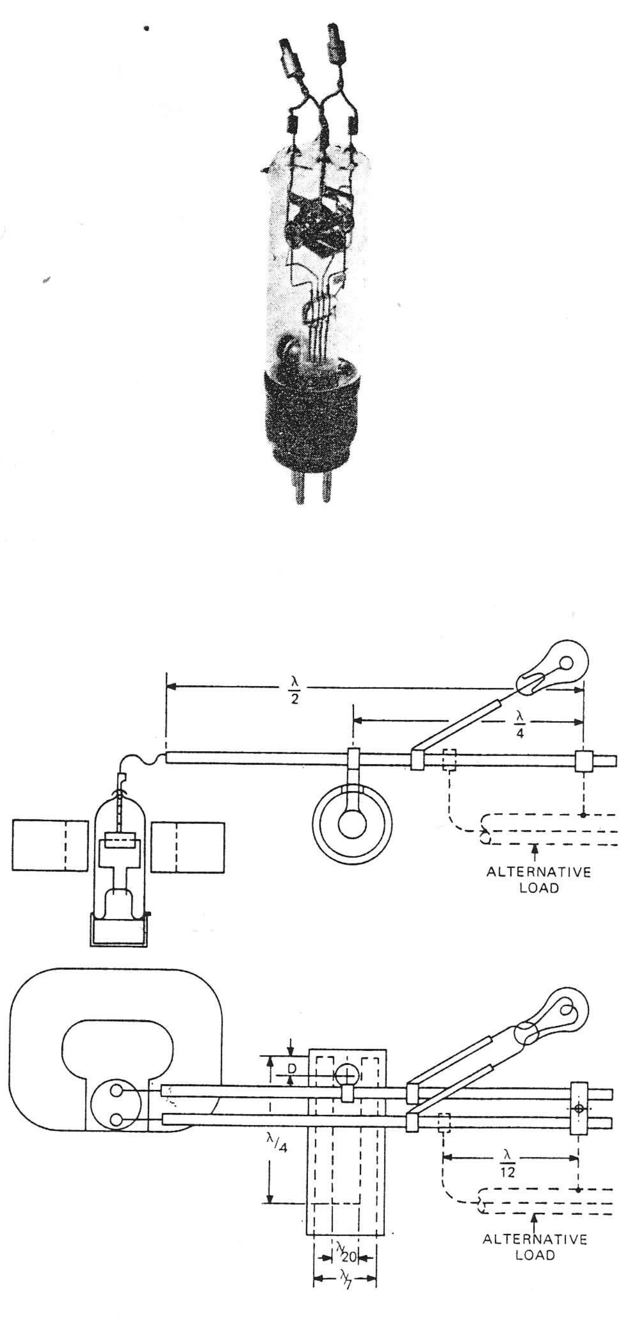


Fig. 2. Magnetron valve and circuit used for communications transmitter, 1937

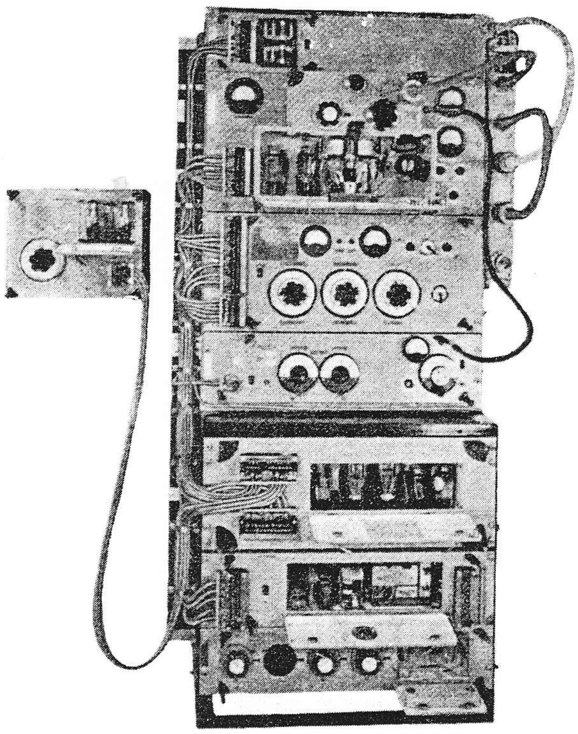


Fig. 3. Communications transmitter, 1937

and Gutton of SFR in Paris, it was concluded that a much larger cathode might be used in multi-segment valves without loss of efficiency. It was agreed that samples of the M16, Gutton's 8-segment resonant segment valve, figure 4, should be fitted with large cathodes, and sent to this country.

COPPER BLOCK ANODE

Shortly afterwards, Megaw made contact with Randall and Boot at the University of Birmingham, when it was disclosed that a 6 gap copper block magnetron operating at 9.9 cm wavelength had been made(9), having a tungsten filament cathode of diameter about 6% of that of the anode, and giving an output (c.w. or pulsed) of 150 watts. This made use of 6 resonant circuits machined out of a solid copper block forming the anode, figure 5(a), through the centre of which a wire cathode was mounted. Power was extracted through a concentric line coupled to a loop in one of the cavities. The valve was continuously pumped and was operated in an electromagnet, figure 5(b).

Design of unstrapped valve

Megaw immediately designed a sealed-off version with improvements resulting in a considerable reduction of the 50 lb magnet weight, and substantially repeating the performance of the Birmingham valve. He then decided to improve the design further by incorporating a large diameter thoriated tungsten spiral cathode, and reducing anode length so that an existing 6 lb permanent magnet could be used. All this was done under the stress of wartime pressure.

At this point, in May 1940, samples of the French M16 were brought to Wembley. As agreed, they had been fitted with large diameter oxide coated cathodes and tests showed a pulse power of the order of 1 kW at 16 cm wavelength, with efficiency up to 15%. Accordingly it was decided to incorporate both thoriated tungsten spiral cathodes and oxide coated cathodes in the Wembley design of large cathode valve. Both were completed together and showed similar results, an output of the order of 1 kW peak being obtained at 5–40 μS, 50 p.p.s. at 9.8 cm wavelength using a 5 lb permanent magnet, figure 6(a). This was on June 29, 1940. Within a fortnight, an output of about 10 kW had been measured in a water load, using the higher magnetic field of an electromagnet. After detailed measurements, it was decided to modify the design so that the higher power could be obtained with the lower field permanent magnet. The number of segments was accordingly increased from six to eight. Figure 6(b) shows a section of this valve which was standardized for Naval use at around 10 cm wavelength. This was the NT 98.

A copy of this was sent to the USA in August, 1940. A variant operating at 9.1 cm was then produced for the first centimetric airborne interceptor (AI) equipment for airborne use.

As soon as the design requirements for valves capable of meeting operational requirements had been established, contact was made with the BTH Research Laboratories at Rugby, where work had been proceeding on high power klystrons. As a result, effort was transferred to the development of the copper block magnetron and its production. This contact between GEC and BTH groups was maintained until long after the end of wartime.

A number of teams were set up at Wembley to construct magnetrons needed by the Services and to study their performance since experience in use showed defects limiting system performance. Nevertheless, large numbers of valves of this and later types were produced in the laboratories, allowing time for factory production facilities to be established elsewhere.

This design was the basis for a range of magnetrons produced in this country and in the USA with little change in constructional details. From this time, very close contact was maintained with the USA, resulting

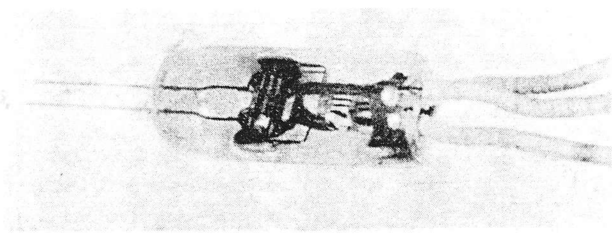
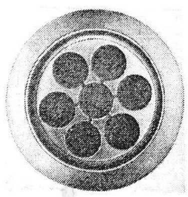
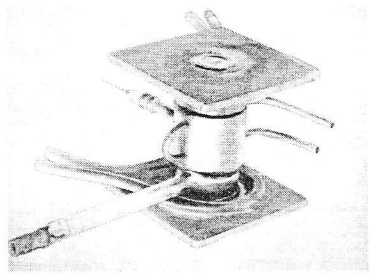


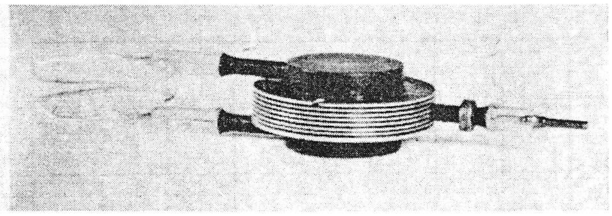
Fig. 4. Gutton resonant – segment magnetron, type M16, 1940



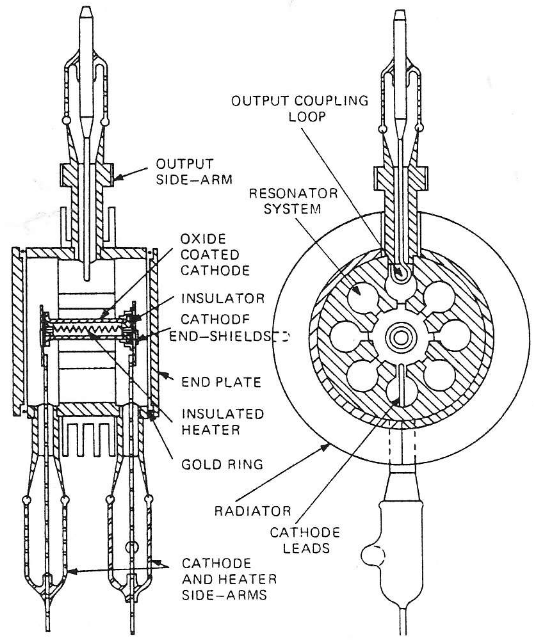


a) b)

Fig. 5. (a) The anode block of (b) the first British 10 cm magnetron



a)



b)

Fig. 6. (a) Magnetron type E1189, the original design for operation in aircraft (b) magnetron type NT98

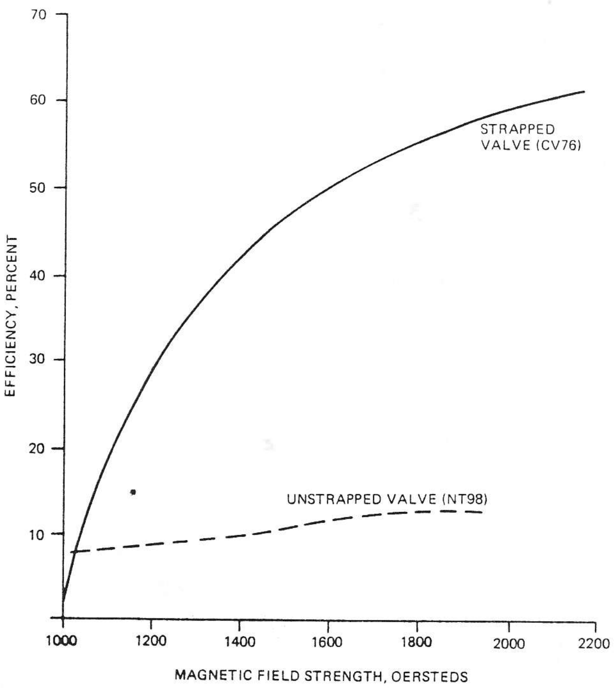


Fig. 7. The effect of strapping on efficiency

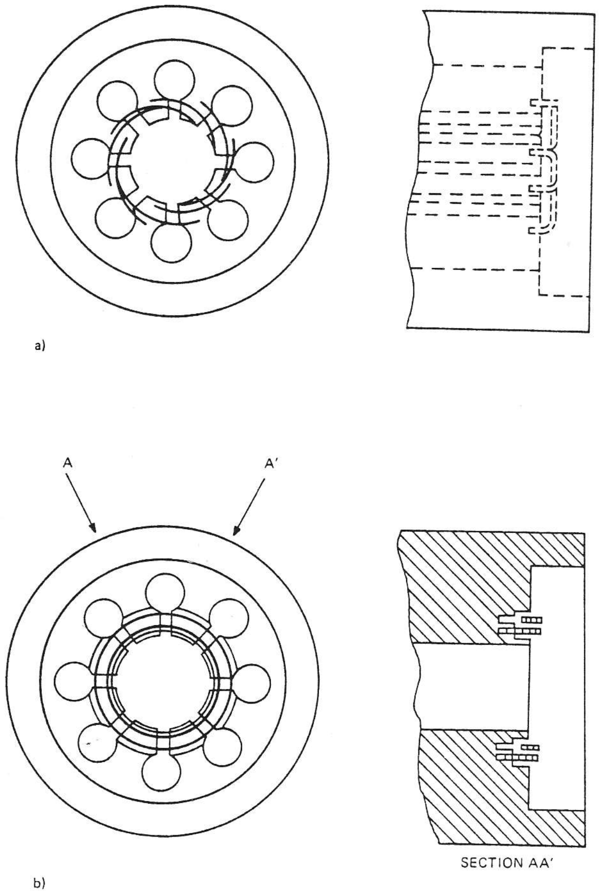


Fig. 8. Methods of strapping (a) echelon strapping (b) double ring strapping (recessed). The same system is used at both ends of the block

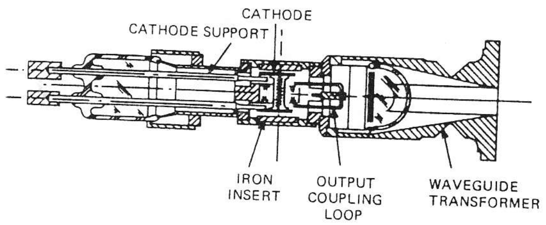


Fig. 9. Section through high power 3 cm magnetron, type CV355

in many new design and constructional features being transferred to this country as the very large American effort developed.

STRAPPING

Experience in the use of this early design showed that with change of r.f. load or operating conditions, the frequency generated could change discontinuously. In 1941, Sayers of the University of Birmingham showed that this resulted from the excitation of the different modes of resonance of the multi-cavity anode in which successive cavities operated with phase differences less than the optimum value of π. He showed that by joining alternate segments together by wires, stability and efficiency were greatly improved[9]. In the NT 98 magnetron, for example, the efficiency had seldom risen above 25% even at high magnetic field, whereas by this technique, an efficiency of 40% could be obtained at a magnetic field of 1500 oersteds and 50 to 60% at 2000 oersteds, figure 7. This established the technique of 'strapping' as a necessary design feature, and various forms were incorporated in established designs as soon as possible. Figure 8 shows two forms of strapping[10].

DESIGN FOR 3 cm OPERATION

Work at wavelengths shorter than 10 cm started soon after the NT 98 was established, but during 1941 there was urgent need for operation around 3 cm. Early designs were based on the established unstrapped 10 cm valves but the increased number of cavities necessary to provide the required cathode area led to increased problems with mode change and efficiency[10]. With a 12-slot 10.5 mm anode and magnetic field of 2670 oersteds, efficiencies up to 20% were obtained with 150 kW input power, but stability problems were numerous. However, experience with smaller strapped valves showed that efficiencies of 30–40% could be obtained at the same input level with an anode of 8.0 mm diameter, with complete freedom from mode change. Figure 9 shows the main features of a 3 cm high power valve. It has a power output of at least 200 kW with efficiency of 40%, operating at 22 kV, 23 A. The anode has 14 cavities double ring strapped and it operated in a magnetic field of 5500 oersteds, obtained from an external magnet, with iron inserts inside the valve envelope. Power is radiated from a loop connected to the straps, with the output waveguide enclosed by a glass dome.

Developments at 3 cm involved not only scaling down dimensions in proportion to wavelength but also increasing the magnetic field, approximately inversely as the wavelength, leading to the need to reduce the magnetic air gap. This was done in the USA by building in pole pieces at each end of the anode block, and attaching 'C' shaped magnets to each end. The cathode was supported at one end through a hole in the pole piece resulting in the 'packaged' valve of figure 10. This packaged arrangement became the standard for 3 cm valves, both for low and high power.

PERFORMANCE OF PRODUCTION TYPES BY 1945

The performance achieved by 10 cm types may be summarized as shown in table 1[10]. These operated with pulse lengths of 1 to 2 μS and repetition rates of 500 to 1000 pps.

The number of types established in production for 3 cm operation was much less than for 10 cm. First, unstrapped designs were produced, to be followed by strapped designs as the increased complexity was mastered. All operated at around 14 kV, with efficiencies in the range 20–40%, with 1 μs pulses at 1000 p.p.s. (typically). An external magnet was used. Coupling to the output waveguide was from a glass enclosed probe coupled to the 'preplumbed' section of waveguide, as in the CV 214 illustrated in figure 11.

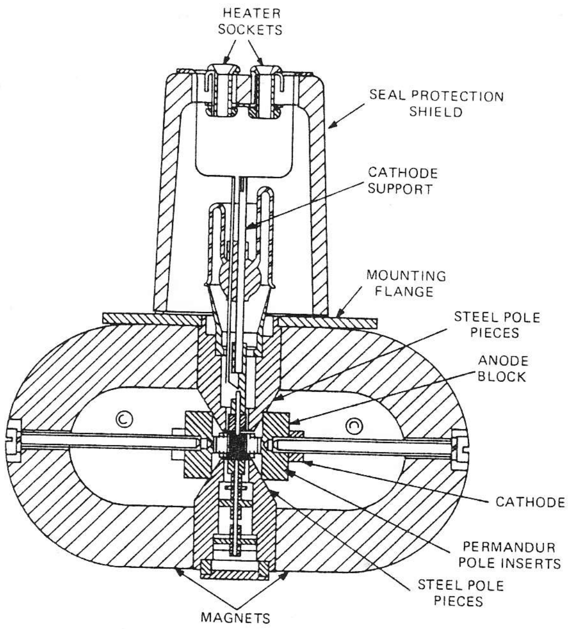


Fig. 10. Section through magnetron type CV348

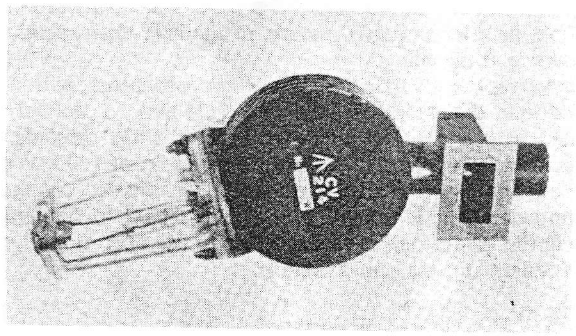


Fig. 11. Magnetron type CV214

MECHANISM OF ENERGY TRANSFER

Once the success of the multi-cavity design had been demonstrated, a considerable theoretical effort was applied, especially at the Universities of Manchester and Leeds and at MIT in the USA to try to understand the parameters of importance in design. In combination with the results of experimental work, the picture eventually emerging was as follows.

When the valve is oscillating in the so-called 'π mode' with the currents in adjacent cavities in antiphase, a standing wave of potential exists round the anode. This may be considered as made up of oppositely rotating travelling waves of angular velocity w/n where n is the number of pairs of segment gaps.

Electrons leaving the cathode under the influence of mutually perpendicular electric and magnetic fields, travel around the cathode with velocity

TABLE 1

Performance of 10 cm magnetrons

	Wavelength cm	Input (peak) kW	Input (mean) W	Efficiency, %
NT 98 (unstrapped)	10	75	38	10
CV 56	10	225	225	40
CV 76	10	1000	1000	50
CV 99	8.5	1000	250	50
CV 64	9.1	130	330	30
CV 192	9.1	600	480	40
CV 69	9.1	1000	250	50
V 160	9.8	500	500	50
CV 41 (unstrapped)	10.7	1000	500	15
CV 120	10.7	1000	500	35

approximating to the ratio of these fields. Providing wave and electron velocities are approximately equal, continuous energy interaction results in a transfer of energy from the static electric field to the rotating r.f. field and thence to the load.

At suitable high magnetic fields, high efficiency results, as it does with a large number of segments, though this leads to the need for special attention to the mode problems which can result. The great attraction of the magnetron has always been the high efficiencies obtained in a 'simple' diode structure, with its resulting compactness.

RISING SUN DESIGN

As the working frequency of magnetrons increases, strapping becomes increasingly impractical. The need to avoid mode change problems other than by the use of strapping led to the invention of the 'rising sun' anode, of section shown in figure 12[11]. In this, the usual system of equal cavities is replaced by one with two sets of cavities of different size, by means of which the desired separation of frequencies of the 'ifferent modes, as well as operating voltage, may be achieved. Such a system is particularly suited for shorter wavelengths, especially since it avoids the use of small delicate straps and because it makes the use of a large number of cavities more practicable. Valves using this arrangement were developed during the latter part of 1945, demonstrating their potential for shorter wave operation, especially for millimetre waves.

In the AX9 of 18 cavities operating at 3.1 cm, a pulse power of nearly 1 MW was achieved, with mean power around 240 watts. In the design shown in figure 12, output power was taken from the back of one of the cavities by a slot, coupled through a slot output transformer into a vacuum enclosed output wave-guide. This waveguide output system has been used in many other designs.

LONG ANODE DESIGN

Around 1950, the need arose for a valve of much greater mean power at 10 cm wavelength than then available (approx. 500 watts) and attempts were made to meet this by designing strapped valves operating at higher voltages, around 40 kV. However the power limit set by electron bombardment of the cathode led to a different approach by Boot at SERL Baldock, resulting in a design known as the 'long anode' valve[12]. In this, anode and cathode length, normally kept less than half an operating wavelength, were greatly increased to avoid the cathode power limitation. Problems of mode change were avoided through the use of a symmetrical output system and very careful design to avoid the effect of axial modes. An anode length of about a wavelength was used. The symmetrical coupling to the output system was achieved by coupling the ends of alternate cavities together to a common probe, which radiated to the output waveguide. The long anode necessitated a solenoidal magnet, so that magnet, magnetron, and waveguide were designed as one unit.

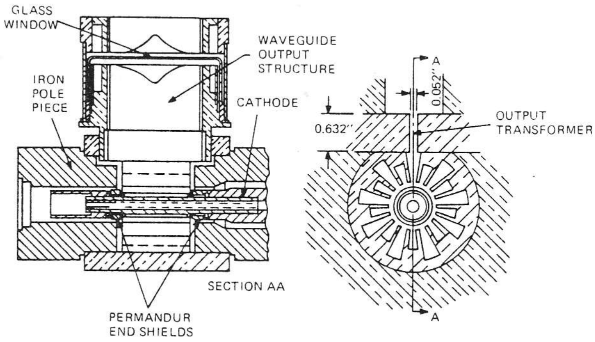


Fig. 12. Cross-sections of AX9 magnetron

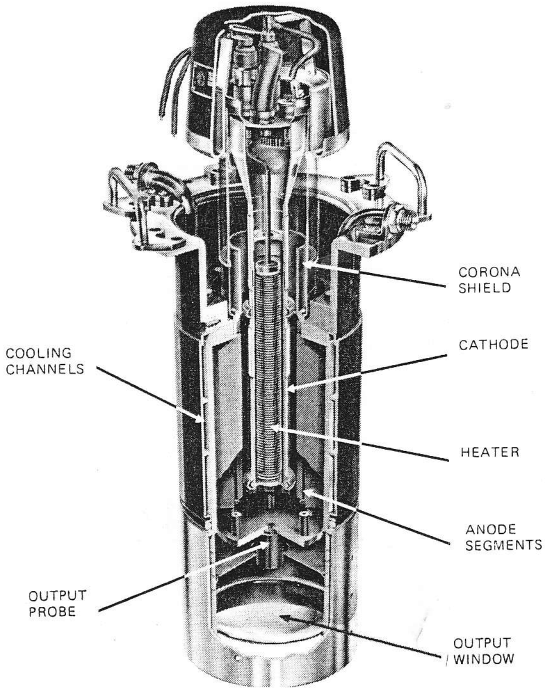


Fig. 13. Magnetron M565, giving 5 MW output in frequency range 1215–1365 MHz

Using these ideas, the design was developed and finally engineered by the English Electric Valve Company to give a power at 10 cm wavelength of 5 kW mean, 2.5 MW peak at 2 μs and 5 μs pulse length, operating at 50% efficiency with a voltage of 40 kV. Figure 13 shows a design for 23 cm wavelength, 30 kW which was also demonstrated.

COAXIAL DESIGN

In the early 1950s, it was clear that in spite of the attraction of the magnetron as an efficient, compact high power source, residual problems of stability against mode change needed to be overcome if the full potential were to be achieved, especially at shorter wavelengths. The structure now known as the 'coaxial magnetron' was devised by Feinstein and others. In this design the currents in alternate cavities were locked in phase by strong coupling to a surrounding resonant coaxial cavity, whose frequency could be adjusted by change of length[13]. Such a system, shown in figure 14, proved very successful, though the coupling to an additional multi-mode cavity results in additional possible modes of operation, which were controlled by resistive damping. The design was particularly suited for operation at the highest frequencies and resulted in higher efficiencies and lower pulling and pushing figures. At 10 GHz, a power of 1 MW was obtained with an efficiency of 65% and a tuning range of 12%, with 100 kW at 50 GHZ. This system is especially suited for rapid mechanical tuning.

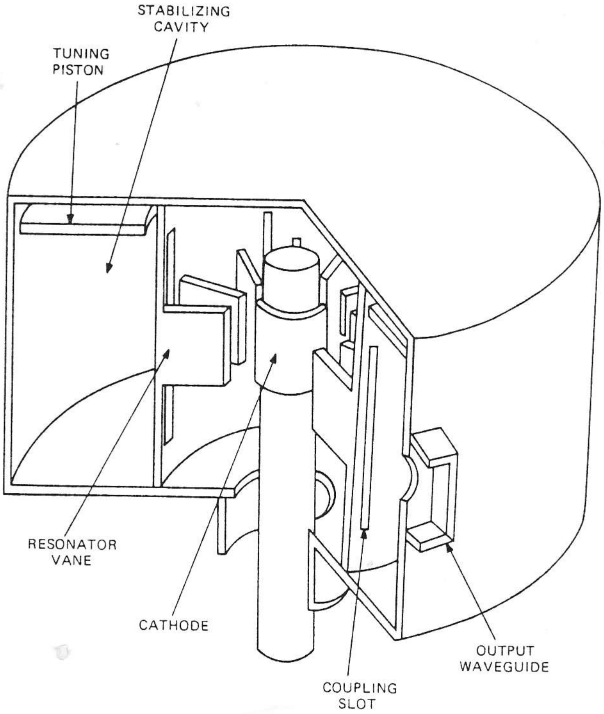


Fig. 14. Principle of the coaxial magnetron

C.W. OPERATION

Although attention has been concentrated here on valves for pulsed operation, designs have also been developed for c.w. use for communication and counter measures. Though operated at much lower voltages they have given mean powers of the same order as the pulsed designs. They have been fitted with tuners operating by changing the effective dimensions of the cavities, and covering a range of 10% and upwards.

RUGGED LOW POWER

Apart from the steady increases in power generated at a given wavelength, there have been striking advances in the performance of low power rugged valves. These follow improved understanding of the factors controlling speed of oscillation build up, and the introduction of new magnetic materials and techniques of mechanical design. Such valves are needed for missile, beacon and guidance systems demanding use under conditions of extreme vibration and shock. Figure 15 shows the general design of a 3 cm valve, one of a range developed by the M. O. Valve Company Ltd. It develops 5 W mean output (150 W peak) having a mass of only 50 g and volume of 10 ccs. It operates at 850 V with 16% efficiency. It has a warm up time of only 2 secs and satisfies many stringent performance requirements.

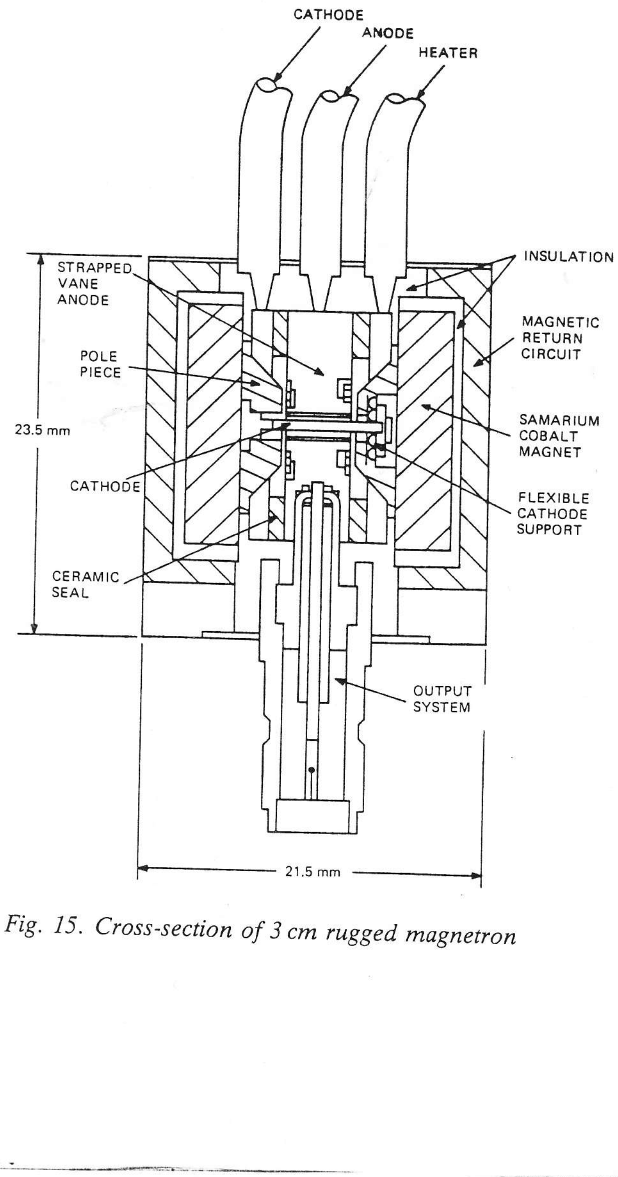


Fig. 15. Cross-section of 3 cm rugged magnetron

MILLIMETRE WAVE VALVES

With the establishment of rising sun and coaxial designs, the major problems in operation were overcome, and the way was open to reducing operating wavelengths to a few millimetres. However, problems of steeply rising atmospheric and rain absorption at wavelengths much below 1 cm inhibited the use and development of millimetre radar and valves. Nevertheless, the narrow aerial beams readily obtainable coupled with use under conditions where the effect of atmosphere absorption is not overriding, has led to development down to a few millimetres. Figure 16 shows a production valve for 3.3 mm having a peak output of 2.5 kW (1.25 W mean). It operates with 50 ns pulses (down to 4 ns) at an efficiency of 4%. It has an integral samarium cobalt magnet and a weight of 2 lbs.

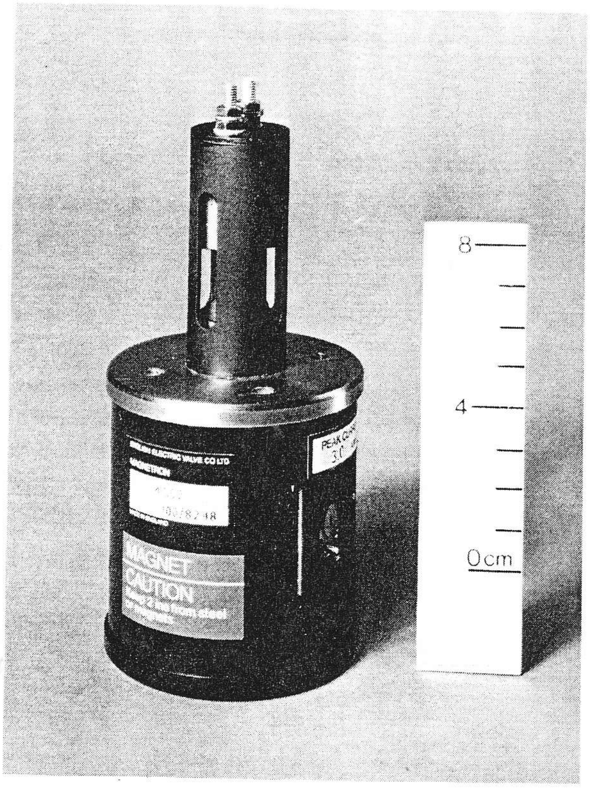


Fig. 16. Magnetron for 3.3 mm wavelength

CONCLUSION

In this very brief summary of the evolution of the magnetron from its chance birth in 1921 to its becoming the key component in many systems, the technologies of construction have been taken for granted. However, the huge effort applied to these technologies, both for magnetrons and other microwave devices, has ensured that the continually refined systems requirements can be met.

For example, insulator materials and technology have been developed to withstand the high voltage stresses involved, to hold components in their required relative position, to conduct heat away, and to enable the high microwave power densities to be transmitted with minimum loss.

Since the cathode is subject to significant electron bombardment, thermionic emission is not usually a problem, though design for adequate cooling is necessary. However the possibility of arcing due to high voltage stress at the surface leads to the need for a rugged surface.

The use of permanent magnet materials of high performance in 'package' structures has led to much ingenuity in integrating these with the rest of the valve elements to enable both electrical and mechanical performance needs to be met.

REFERENCES

1 HULL, A. W., 'The effect of a uniform magnetic field on the motion of electrons between co-axial cylinders', Phys. Rev., *18*, p. 13, 1921.

2 ZACEK, A., 'Uber eine Methode zur erzeugung von sehr kurzer elektromagnetischen Wellen', Zeit f. Hochfrequenztechn., *32*, p. 172, 1928.

3 HABANN, E., 'Eine neue Generatorrohre', Hochfrequenztech. 24, p. 115, 1924.

4 OKABE, A., 'The short wave limit of magnetron oscillators', Proc. I.R.E., *17*, p. 652, 1929.

5 MEGAW, E. C. S., 'An investigation of the magnetron short wave oscillator', J.I.E.E., *72*, p. 326, 1933

6 POSTUMUS, K., 'Oscillations in a split anode magnetron', Wireless Engineer, *12*, p. 126, 1935.

7 MEGAW, E. C. S. and WILLSHAW, W. E., 'An early application of decimetre waves to communications between ships' 'Atti del Congresso Internazionale per il Cinquatenario della scoperta Marconiana della Radio' 28 settembre-5 ottobre, 1947.

8 MEGAW, E. C. S., 'The high power pulsed magnetron: a review of early developments', J.I.E.E., *93* Part IIIA No. 5, p. 977, 1946.

9 BOOT, H. A. H. and RANDALL, J. T., 'The cavity magnetron', ibid., p. 928.

10 WILLSHAW, W. E., RUSHFORTH, L. et al., 'The high-power pulsed magnetron. Development and design for radar applications', ibid., p. 985.

11 MILLMAN, S., 'Microwave Magnetrons', McGraw-Hill, 1948, p. 470 and p. 785.

12 BOOT, H. A. H., 'Long anode magnetrons', Crossed-field Microwave Devices, vol. 2, Academic Press, p. 261, 1961.

13 FEINSTEIN, J. and COLLIER, R. J., 'The circular electric mode magnetron', ibid., p. 123.

SESSION III

Chairman: **Professor D. C. Colley**

INVITED TALK

GEC's Wartime Contribution

Mr W. E. Willshaw

Introduction

I am glad of the opportunity to talk about the contribution of the GEC Research Laboratories to the research on and development of the cavity magnetron.

The laboratories at Wembley were opened in 1923 following the company's decision, during the First World War, to found laboratories covering fundamental problems arising in the manufacture of electrical products and to pursue research on new products. Experience in wartime had shown how dependent this country had been on research carried out abroad. This was the first research laboratory in this country specifically for the electrical manufacturing industry, with control independent of product manufacture.

The laboratories were built on a green field site in north Wembley, with ready rail access to London for scientific meetings. Its founder was C. C. Paterson, who had strong views on the facilities and organization needed. He came from the NPL, where he was in charge of the Electrotechnics Department and Photometry, and was Director at Wembley until his death in 1948.

Early work on magnetrons

In 1937 I joined Eric Megaw at Wembley where he had worked since 1930 on valves for the shortest possible wavelengths. He was convinced that the magnetron diode offered the best opportunity for this. He was very familiar with work in progress in Europe, especially in Czechoslovakia, Germany, France, Holland, in the USSR, and in Japan and the USA.

In the period since 1924, three distinct modes of operation were recognized for the magnetron diode and its split-anode versions. These were the electronic mode with frequency dependent on magnetic field only, the dynatron mode with negative resistance both at low and higher frequencies, and the travelling-wave mode, which is our concern today. There was considerable confusion in interpreting operation, arising especially from the overlap of the latter two modes. But in 1934 Posthumus in Holland developed a successful four-segment magnetron and published his travelling-wave theory. This was followed by Megaw and Herriger and Hulster with ideas on precessional resonance between electron orbits and a standing wave of potential round the anode, establishing a basic procedure for design. It was used for several years before the War.

In this, no special reason was seen for the cathode diameter to be limited to a small fraction of the anode diameter, but almost all valves used tungsten filament cathodes which were quite adequate for early CW needs. Indeed early German data on the use of large tungsten spiral cathodes indicated a fall in efficiency and this misleading result was widely believed.

Early use for communication

In 1937 a four-segment glass-envelope valve (E880, NT75) was designed at Wembley, and used at 40-60 cm in a study for the Admiralty. This had an anode diameter of 7 mm, a thoriated tungsten cathode of 0.25 mm, giving an output around 10 W at 50 cm wavelength. The objects of the study were to confirm that a magnetron self-oscillator could be used in an engineered system and that the communication range would be limited by the horizon, so that ships' receivers could not intercept beyond this range.

A complete system was designed and made at Wembley for shipboard use, with magnetron transmitter, frequency stabilized by a resonator, stabilized power supplies, square-wave modulator and super-regenerative receiver using an acorn signal oscillator. After initial-local trials, twelve sets of equipment were built at the GEC Telephone Works at Coventry and installed in a variety of ships including a capital ship and a flotilla of destroyers. They were used in wartime and after one year's experience judged to be most successful in operation. It was concluded that a magnetron could be used in an operational system, providing adequate care was taken in the provision of stable power supplies and frequency stabilization. Figure 1 shows the transmitter with magnetron and all its stabilizing equipment.

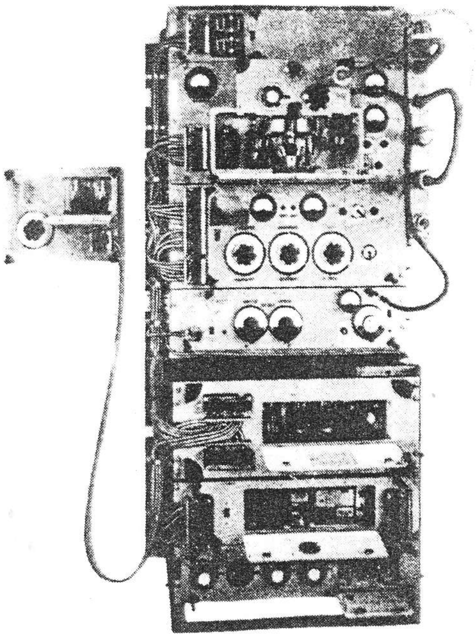


Fig. 1
Complete transmitter, with output attenuator, keying load absorber and frequency meter

Work on multi-segment magnetrons

In 1938, Gutton and Berline of SFR in Paris reported the performance of their recent multi-segment valves. The anode was formed of a self-resonant interdigital system of between six and eighteen segments and the cathode a tungsten filament. Efficiencies between 10 and 15% were obtained over the range 10-20 cm. These results were discussed with Megaw during a visit to Paris in 1939 when it was arranged that samples would be sent to him. The outbreak of war delayed this.

A few weeks later contact was made with Randall and Boot at Birmingham who had demonstrated their six-segment copper-block valve, operating on the pump, giving a power of 150 W CW at 9.9 cm wavelength with 7 kV, 0.15 A input. The magnetic field of 1300-1400 Oe was produced by a large electromagnet of 13 cm air gap. A 0.75 mm tungsten filament was used in a 12 mm diameter anode, 40 mm long. Figure 2 shows a section of the anode block. Figure 3 shows this tube, which was water cooled.

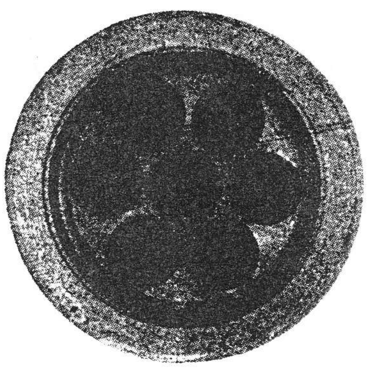


Fig. 2
One of the first six anode blocks made

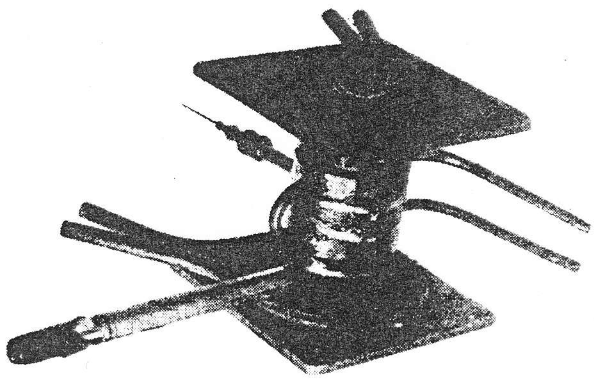


Fig. 3
The first (demountable) cavity magnetron

In discussing the design, Megaw suggested that it could be simplified, and the magnet weight greatly reduced, by using metal ends to close the block and side-arm supports for the cathode. In collaboration with Randall and Boot he produced a sealed-off valve with these changes, fitting a 7 cm magnet gap. Its performance was similar to that of the Birmingham valve and reached 500 watts CW, limited by emission from the tungsten- filament cathode.

In this design the gold-seal technique, originated in Wembley a few years before, was used as a clean and simple method of attaching the copper end discs to the block, after mounting the cathode on side arms. Figure 4 shows this completed valve, called the E1188 No.1.

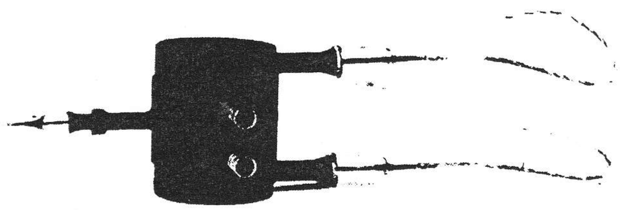


Fig. 4
E1188, No. 1. Improved model of Randall-Boot tungsten-filament magnetron; designed and made in collaboration with Birmingham University (Design completed 16th May, 1940).
CW or pulse output of the order of 0.5 kW at 10 cm. Electromagnet, weight 50 lb

Following increasing demand for a 10 cm valve for airborne use, it was then decided to make a design more suited for this. It had a large-diameter thoriated-tungsten spiral cathode, and a shorter anode length so that an existing small permanent magnet could be used. Air cooling replaced the water cooling of the earlier valve.

In May 1940, two samples of Gutton's 16 cm valve arrived. They had twelve segments, 10 mm anode diameter and had been fitted with 4 mm diameter oxide-coated cathodes. They had already given a pulse power of 1 kW. An emergency pulse modulator was built giving 200-2000 µs pulses at 50 p.p.s. and measurements made over a range of magnetic field and current. In particular it was found that oscillations could be maintained with a primary emission less than 1% of the anode current, confirming the importance of secondary emission with the oxide-coated cathode, as discovered at Wembley in 1933.

In addition, two ranges of operation were observed with a wavelength difference of 2%. These were interpreted as corresponding to twelve-segment and six-segment oscillation of the anode system.

In view of these results, two models of the new compact design of 10 cm copper-anode valve were fitted with thoriated-tungsten and oxide-coated cathodes of diameter 3 mm and 4.5 mm respectively in a 10 mm diameter anode. Outputs around 1 kW pulse were obtained on 25th June with the lower-field permanent magnet of 1100 Oe and 10 kW with 1400 Oe from the electromagnet. The wavelength was near 9.8 cm for both valves. In view of all these results, the use of the oxide-coated cathode was regarded as established.

Final design of the first copper-block magnetron

The new design was basically satisfactory, except that the magnetic field for maximum efficiency was too high for the existing permanent magnet. Accordingly the design was recalculated for eight cavities instead of six, keeping the wavelength at 10 cm. The modified design, now E1189, was standardized for naval use (NT 98). Figure 5 shows this and Figure 6 shows a section of the construction. E1198 (CV38), a variant for 9.1 cm operation, was used in the first airborne equipment.

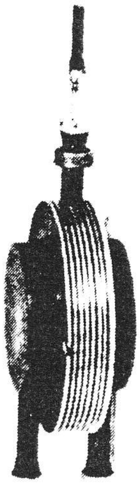


Fig. 5
Magnetron type E1189, the original design for operation in aircraft

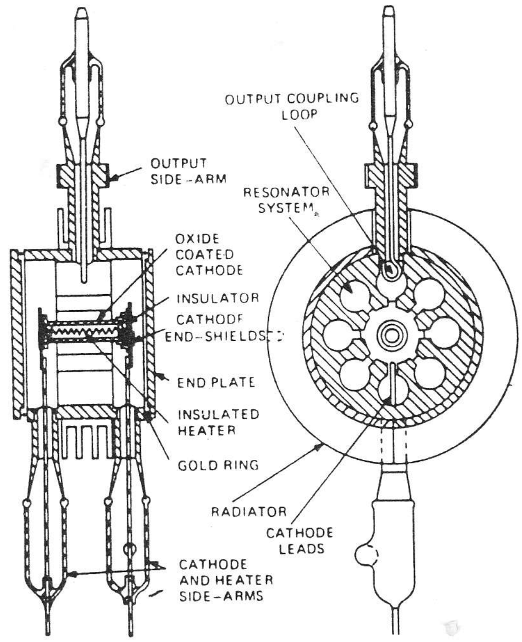


Fig. 6
Magnetron type NT98

The first sample of the E1189 was taken to the USA by the Tizard Mission in August 1940.

By now the basic requirements for production for both naval and aircraft use had been solved, though there were still problems in stable operation.

The work at Wembley was greatly extended by the setting up of pre-production teams of scientists and assistants. As a contribution to the national effort the Patent Department had been closed down at the start of the War and provided staff of both types, as did other Departments. The Research Laboratories of the BTH at Rugby, which had been associated with the earlier Birmingham work on high-power klystrons, had also started work on magnetrons and a close relationship was formed with GEC, with regular meetings on current problems. The later work described here, particularly on 3 cm valves, benefited greatly from this collaboration.

By the end of 1941, when newer types began to appear, about 2000 valves of the NT98 type had been produced.

Mode change and strapping

With larger numbers of valves in use in equipment, defects in operation became apparent, especially those due to mode change. These resulted from the use of several cavities to increase anode and cathode size and therefore power.

With N cavities, the mode of oscillation with π phase change between adjacent cavities resulted in $N/2$ repeats of RF field round the anode, with N even. This mode number could vary from $N/2$ down to one with small frequency change and any one of these modes might be excited.

In 1941, Sayers at Birmingham investigated this and evolved a relatively simple method of separating the frequencies of the modes. This involved connecting together, by short lengths of wire, those cavities required to be in phase, and was remarkably effective at least for wavelengths around 10 cm. Figure 7 shows the separation achieved in a typical eight-cavity valve.

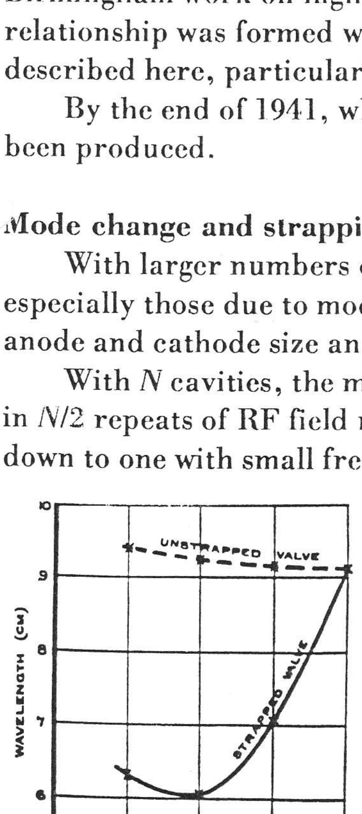


Fig. 7
Mode spectrum of unstrapped and strapped valves

Separation of frequency was not the only requirement for stable operation, as discussed later, but a big increase in efficiency followed. The 10 cm E1198, which was not strapped, operated at 7.5 kW output with 10% efficiency. The strapped version CV56 operated at 90 kW output with 40% efficiency.

The preferred π mode was now excited at much lower voltage than the other modes, though these could still be excited by Fourier components at lower voltages.

This improvement by strapping meant that large increases of power could be obtained, without change in anode design, provided that improvements were made to the heat dissipation of the cathode, amounting to 3-6% of the mean anode power, as a result of cathode bombardment.

The resulting CV76 operated at 500 kW output with 50% efficiency, the coupling to the output waveguide being by direct RF radiation from the output probe. It was used extensively in naval and ground radar. Similar designs were produced for 9.1 and 8.5 cm with the same power and efficiency.

Contact with theoretical groups

During the work at Wembley, close collaboration was developed with Professor Hartree's theoretical group in Manchester. One result of the Manchester work was an expression for the threshold anode voltage which must be exceeded if electrons are to reach the anode in the presence of cavity oscillations. Good agreement was obtained with experimental values, as indicated in Figure 8, as well as with those arrived at by earlier simple calculations. This figure shows threshold voltage as a function of magnetic field for different modes of an eight-cavity valve.

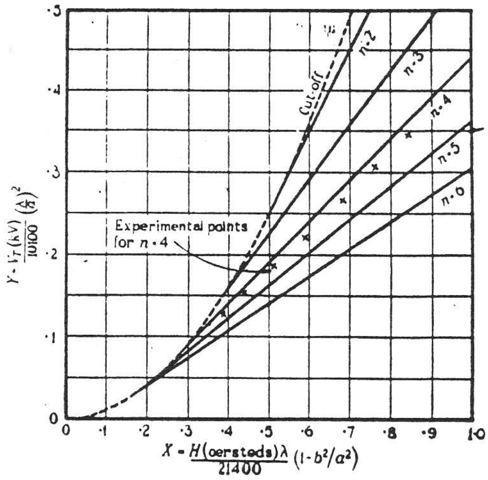


Fig. 8
Relation of threshold voltage to magnetic field-strength for various values of n

These values of threshold voltage led to the identification of modes observed after mode change, and the realization that higher-order Fourier components could be excited at voltages close to that of the π mode.

Understanding of the mode-change problem was, however, aided by the concept of the instability voltage. This is the voltage necessary for small signals to be generated to initiate the oscillations necessary for the threshold voltage to be effective. In practical valves these are not very different and their relative values are dependent on the ratio between anode and cathode diameters. Thus conditions may be found to allow operation in the required mode over the required current range. Figure 9 shows the relation between theoretical and experimental current range for

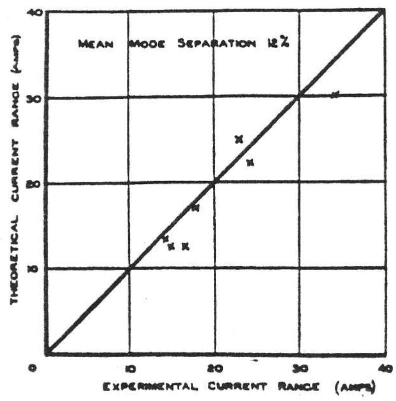


Fig. 9 *Relation between theoretical and observed current-range for 3 cm magnetron*

different cathode sizes in a later 3 cm magnetron. This theory was of considerable value in designing new valves and in modifying the performance of existing ones.

One result of the calculation of electron orbits in the presence of space charge was the realization that at the high magnetic fields necessary for good efficiency, electrons arrive at the anode surface with a tangential velocity close to that of the rotating wave with which they are interacting. Those returning to the cathode do so with small energy since their penetration into the anode field is small. This results in a simple expression for maximum efficiency, which is in reasonable agreement with experience for high magnetic fields.

Figure 10 shows theoretical and experimental values for a typical eight-segment valve, allowance being made for the RF power lost in bombardment of the cathode. This shows the very high efficiencies which may be obtained.

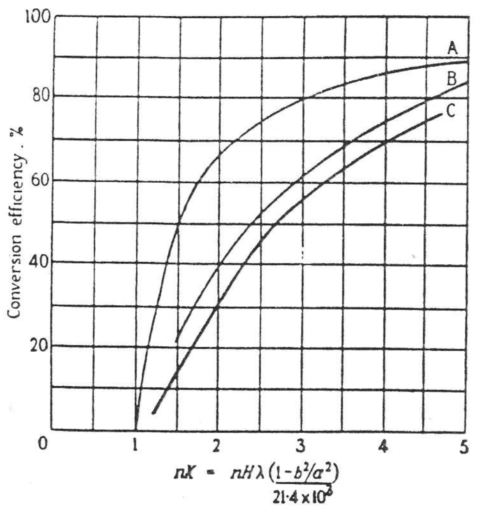


Fig. 10
Theoretical and measured efficiencies,
A, Theoretical efficiency; B, Measured efficiency for a typical 8-segment valve; C, Mean (measured) curve for a large number of designs

Higher-power valve for 10 cm

Towards the end of 1942 there was a demand for a 10 cm valve of 4-5 times the 500 kW then available. The development took a long time due to continuous mode-change problems. Many trials were made with large anode and cathodes, heavy strapping for large mode separation but without success in reaching the current required. Eventually the significant factors already mentioned, controlling mode change, were sufficiently understood to enable the required power to be reached and Figure 11 shows the valve produced. This had 10 segments operated at 40 kV, 100 A with 2000 Oe field and gave at least 2 MW. It was air cooled, with a waveguide output system coupling to a 3" x 1" waveguide, through a taper system.

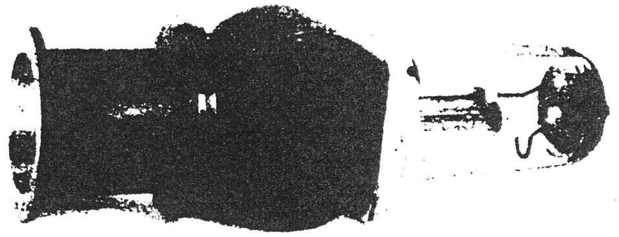


Fig. 11
High-powered air-cooled 10 cm magnetron

Valves for 3 cm

In 1941 there was a need for operation around 3 cm. At this time little of the work on stable operation of 10 cm valves had been done, especially on the use of strapping, but it was known to be necessary to increase considerably the number of cavities or to reduce anode and cathode sizes. Early valves were made with anode sizes similar to those of the 10 cm valves, and with up to 22 cavities with cathode areas only slightly less. The efficiencies were between a quarter and a half of the best 10 cm valves and there were always troublesome mode changes. When the success of strapping had been established, many forms were tried without success.

It was thought that the lower relative accuracy of forming the cavities for 3 cm might be the cause of poor performance, and attention was turned to increasing cavity size. A construction was devised in which the ends of the cavities were closed, as shown in Figure 12. The cavity wavelength was then close to twice the cavity length. Equalizing the wavelengths of individual cavities arose through the machining operation of turning to length. In an early trial, end plates were fitted to a 10 cm unstrapped valve, resulting in oscillation around 3 cm with output of 80 kW at 12% efficiency. In spite of a large number of trials, the scheme was rejected since performance was no less variable than with open-ended designs.

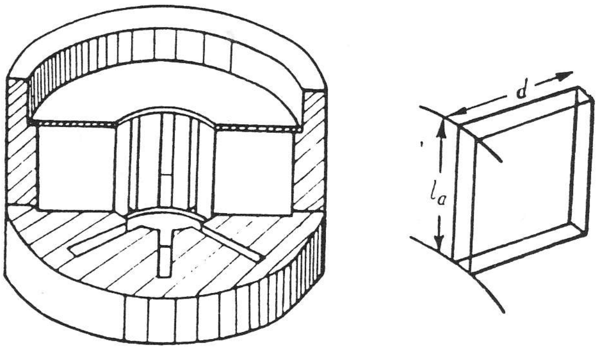


Fig. 12
Closed-end structure

The first developed 3 cm valve, called the CV108, had 18 cavities and was unstrapped. The cavity number was reduced to 12 and ring straps added. Now called the CV208, it generated 30 kW at 20% efficiency and was a complete replacement for the earlier CV108. Experimental valves were produced in August 1943, with pre-production samples in November.

In a modification, part of the load waveguide was added to the valve, output coupling being adjusted in manufacture by a piston closing one end of the output waveguide. A glass cover protected the cathode support. This was called the CV214.

With later needs for higher power, a new design called the CV355 was produced. It generated 200 kW output, with 100 W mean, and had an efficiency of 40%. It had 14 cavities with double ring strapping and operated at 22 kV, 23 A with a magnetic field of 5500 Oe in the valve anode. The cathode was of the oxide-coated type, with metal loading to minimize voltage flashing and was mounted on heavy tungsten supports to minimize vibration. In this design, problems of voltage flashing, mode change, cooling of the cathode and design of output circuit were particularly important.

Thus, since the demonstration of the first practicable 10 cm valve in August 1940, with a few kilowatts pulse output, power of a few hundred kilowatts had been obtained at 3 cm, three years later.

Impact of American techniques and experience

Of course the receipt of the first multi-cavity design in the USA caused a rapid build-up of R and D work and the results were fed back in the shape of advances in materials and constructional techniques, new designs and theoretical work.

Typical were the use of end-supported cathodes and packaged magnets, and the later use of the 'rising sun' anode to avoid the need for straps. Figure 13 shows a selection of later low-power 3 cm valves making use of these features. Figure 14 shows a cross section of the AX9 rising-sun valve. With 18 cavities it gave a pulse power of nearly 1 MW which was achieved at 3.1 cm with 240 W mean power. The power was taken from the back of one of the cavities by a slot into a vacuum-enclosed output waveguide.

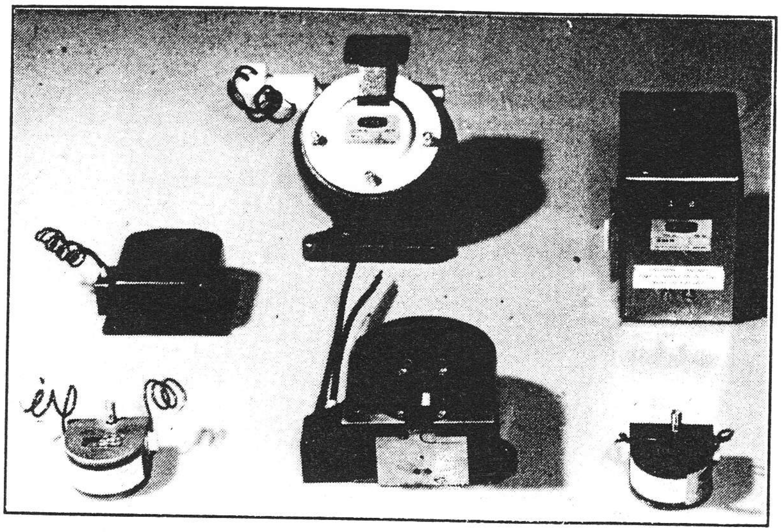


Fig. 13
A selection of low-power 3 cm valves

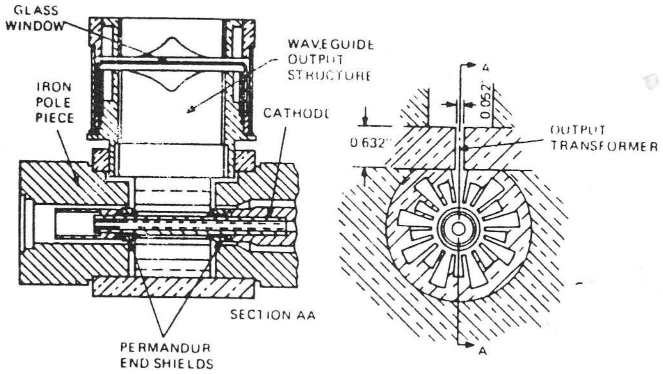


Fig. 14
Cross sections of AX9 magnetron

Conclusion

This review summarizes briefly the GEC's contribution to the progress of the magnetron up to the end of the wartime years, latterly in close collaboration with BTH. Although it concentrates chiefly on designs for radar, there was significant work on CW designs in which relatively wide tuning was achieved mechanically, with similar mean power and efficiency to pulsed valves. This work also led to increased understanding of the magnetron behaviour at very low current.

After the War, work continued on millimetre waves as well as on higher-power centimetre waves.

Reference
Willshaw, W. E., "Microwave Magnetrons: a brief history of research and development". *G.E.C. Journal of Research* 3, No. 2, 1985, p. 84.

DISCUSSION

Professor Colley:

Would anyone like to make a comment on the industrial contributions, or ask a question about them?

Dr Jelley:

You showed a three-centimetre one with end-plates actually sealing. Were the lengths of the slots half a wavelength or something? Why didn't that short it out completely? (Not one that had strapping but one that was actually sealed with flat plates.)

Mr Willshaw:

Well, one looked upon this as a waveguide and so the axial length of the slot was not very significant at all - nothing like as significant as it would be without the end-plates on.

Dr Jelley:

I am surprised that it doesn't short out the RF, because it is unlike the strapping.

Mr Willshaw:

No, the main problem was - of course, we decided this later - that the coupling between adjacent elements was of course much smaller than it was in the hole-and-slot devices. It was only due to a leakage into the cathode space that one got coupling, whereas in the earlier hole-and-slot device one had magnetic field linking into the end-space.

Dr Lawson:

It is not an important point, but I seem to remember hearing somewhere that the Japanese had done some important early work on magnetrons. Of course, we have only relatively recently known about it - is that right?

Mr Willshaw:

Yes, they did quite a lot of work. Okabe was the man who did the work which was published in the United States. It was done in Tokyo, before the War.

Dr Lawson:

What kind of magnetrons were these, then?

Mr Willshaw:

I never really saw any details about that so I do not really know.

Professor Colley:

Most people do by the look of it! [laughter]

Mr Tomlin:

It was rather a surprise at the IEE 1985 Symposium, when the Japanese gave a paper, to see for the first time some photographs, and some actual models and frankly some of them were almost identical with ours. The cavities were the same form, the numbers of cavities were more or less the same. There was one version which was, shall we say, an artist's version, in that all the surplus metal had been cut away between the cavities in order to make a very nice pattern, but had no value at all. But we were very surprised to find that some of these had actually been used as early as 1937 in one of the battleships. So they had in fact got cavity magnetrons long before we had, and you find the article, which is the actual talk that they gave, in the Radar Symposium book 1939-45 issued by the IEE. I cannot give you actual titles I am afraid.*

Mr Burman:

There is also a paper that describes those magnetrons by Nakajima from Japan Radio Company**. I have a copy of it here, but I did not think that it would be appropriate to bring it up today, actually. [laughter]

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*Nakajima, S., "A history of Japanese radar development to 1945" in Russell Burns (Editor), *Radar development to 1945*, Peter Peregrinus (on behalf of the IEE), London, 1988, 243-258. P.M.R.

**Nakajima, S., *The study of the microwave magnetron*, Japan Radio Company, April 1947. Mr Burman has also given details concerning a paper on Russian work: Alekseev, N. F. and Malairov, D. D., "Generation of high-power oscillations with a magnetron in the centimeter band," *J. Tech. Phys.* (Russian), 10, April 1940, 1297-1300: received by the IRE(US), May 22nd 1943 and, as translated by Bensen, I. B., published in *Proc.IRE*, 1944, March. P.M.R.

Actually the question I wanted to ask Mr Willshaw relates to the production of the first eight-cavity magnetron as opposed to the six-cavity version. Your description and your explanation of it that it was required to improve the efficiency within the available magnet, ties up with Megaw's paper presented in 1946. If you read Dr Bowen's *Radar Days*, he has a rather more story-telling type of version. He describes how he turned up at the Bell Telephone Laboratories with the magnetron and they X-rayed it and found that the one that he had had eight cavities and when he rang up Megaw to find out what had happened, he was told "Oh, my goodness, yes, I asked the foreman to make ten anode blocks with six cavities, and one with seven and one with eight and the one with seven was the one that didn't work."

Is that really the case, or it that just a bit of historical nonsense?

Mr Willshaw:

Yes, I think that is just another bit of historical mis-management. There is no point in going to odd numbers of cavities in view of Megaw's earlier experience, although, undoubtedly, the seven-cavity one would have worked quite well but with all the mode-change problems of it, presumably.

Professor Colley:

Thank you, Mr Willshaw. I am afraid that we will have to terminate that discussion.

I will now call on Dr Bryant, from the University of Michigan, whose talk will concentrate on British, American and Canadian collaboration during the War.

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The Cavity Magnetron: Not Just a British Invention

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Abstract

It is a common belief by many people that the resonant-cavity magnetron was invented in February 1940 by Randall and Boot from Birmingham University. In reality, this is not the full story. Rather, it is a point of view mostly advocated by the winners of the Second World War, who gained a great benefit from this microwave power tube (thanks to a two-orders-of-magnitude increase of power) in the Battle of the Atlantic, in night bombing until the final collapse of the German Reich, and in many other operations. This paper discusses the contributions by other nations, mainly France, but also Germany, Japan, The Netherlands, the Czech Republic, the USSR, and even more, to the cavity magnetron and to its roots.

1. The Cavity Magnetron and Its Practical Significance as a Major Innovation in 1940-1945

The industrial development of the cavity magnetron, and the subsequent development of high-power airborne and surface microwave radar, appear as a typical case of "major innovation," i.e., according to the definition often used by technology historians, an invention that leads to practical – and profitable – use serving some recognized need of our society. It has been treated in many books (see, for instance, [1-5]) and in many papers. The most vivid description was probably in [1], a book written by the Welsh physicist, Edward G. Bowen (1911-1991), a prime actor in the development of microwave and airborne radar. Just looking at the titles of these books, it is evident that in many cases the "British (or American) pride" of the winners of the Second World War, as well as the trend to exalt history, seems to prevail over objectiveness and completeness. Some notable exceptions are from Canadian, Italian, and French authors, as in [6-8]. They are among the very few sources mentioning the decision of the British *Air Ministry* to inform – under military secrecy – the *dominion governments* of the most industrialized Commonwealth nations (Canada, Australia, South Africa) of the developments in the field of radar, pushing ahead the development of radar in those nations (see, for instance, the last chapter of [9]).

Like radar itself, the cavity magnetron was "a simultaneous invention" [7] in different nations. However, it is generally recognized that Birmingham University implemented the first high-power version of this microwave device that was easily reproducible and suited for mass production.

Prof. Marcus (Mark) L. E. Oliphant (1901-2000), an Australian physicist, came to Birmingham University in 1937, where he worked on high-power radar under contracts with the British Admiralty. As a matter of fact, in 1938-1940, there were strong requirements to improve the angular resolution of both the airborne radars and the surface radars (metric-wave airborne radars – which were in operation before the microwave magnetron was invented – could only detect targets at a distance less than the height above the terrain of the own aircraft, due to the unavoidable reflections from land or sea). A basic requirement was a power of at least 1 kW at the optimal wavelength, which was evaluated to be approximately 10 cm. It is well known that at Birmingham University, the cavity magnetron was improved by John T. Randall [10] and Henry A. H. Boot, two researchers of Oliphant's group (see Figure 1). On February 21, 1940, their experimental device, sealed by wax and permanently connected to a vacuum pump, and oscillating at a wavelength of 9.8 cm, produced the very significant power of 400 W, two orders of magnitude above the levels previously available at that wavelength. The work at Birmingham proceeded quickly, arriving in a few weeks at power levels of the order of kilowatts (later, in September 1940, Randall and Boot developed a 14-cavity magnetron operating at 5 cm, and another magnetron with six cavities operating at 3 cm; in May, 1941, they succeeded in producing 1 MW at 10 cm: a three-orders-of-magnitude improvement with respect to their first prototype!).

Figure 1. H. A. H. Boot (l) and J. T. Randall in their laboratory after WW II. Boot has in his hands a six-cavity anodic block.

Of course, the early devices by Randall and Boot were laboratory prototypes, not suited for field operation. In April, 1940, the Admiralty signed a contract with the General Electric Company Ltd. (GEC) at Wembley to produce an operational device. First of all, this device was to operate with neither vacuum pumps nor an external generator of the magnetic field. The water-cooled device No. 1 (the following devices were air-cooled) oscillated for the first time on June 29, generating 500 W at 9.8 cm. By mid-August, a bulky prototype of a radar with a 10 cm magnetron and two small paraboloids as transmitting and receiving antennas detected the first microwave echoes of an aircraft [3, 11]. Eric C. Stanley Megaw (1908-1956), team leader of the GEC laboratories, modified some important elements of the Birmingham design, including the coating of the cathode with oxides. Soon, in September, the power reached 100 kW at 10 cm wavelength. The first airborne trials were done with a twin-engine *Blenheim* in March, 1941, and the operational use soon followed.

In mid-1940, with the German troops in Paris and the French armistice (June 14), it was clear to the British that the industrial power of Germany and occupied nations was going to outperform that of the United Kingdom. The UK would risk quickly losing the (more and more technological) war. The authoritative professor and scientific advisor to the British government, Sir Henry T. Tizard (1885-1959), Chairman of the Aeronautical Research Committee since 1933, suggested disclosing the scientific and technical information to the Unites States government, so that their enormous potential for development and manufacturing could be put to effective use. On August 9, W. Churchill approved the project, paving the way for the "British Technical and Scientific Mission to the

United States and to Canada:" in short, the "Tizard mission" [1, 12]. During the mission (August-October, 1940) the cavity magnetron type E1189, series N. 12, developed by E. C. S. Megaw at GEC, was brought to North America by E. G. Bowen [1] in early September. This device was able to radiate 10 kW at 10 cm. Its original schematic is shown in Figure 2.

The cavity-magnetron technology was quickly mastered in the USA. In the fall of 1940, the Massachusetts Institute of Technology created the Radiation Laboratory, which supplied microwave radars to the allied forces, giving them a technological advantage that soon reached two or three years over the German radars. This happened at a crucial stage of the war, giving the allied air forces decisive air supremacy. It opened access to the Microwave Age, and all its promising other applications. This gave to the cavity magnetron invention all the attributes of an exceptional innovation.

Nevertheless, the Birmingham test on February 21, 1940, cannot be dissociated from the long effort which preceded... and followed it. This was the subject of a recent IEEE conference, CAVMAG 2010 [13]. It is worth remembering that Randall and Boot did not invent the magnetron, nor the *cavity magnetron*, as many people believe today (and as they may have thought themselves!). In fact, this miraculous device was the outcome of a worldwide, almost three-decade running story, which has been well documented by many historical books and papers, including [8, 11, 14-17] and the more recent papers of CAVMAG 2010 [13]. Some major steps can be retained from this long route.

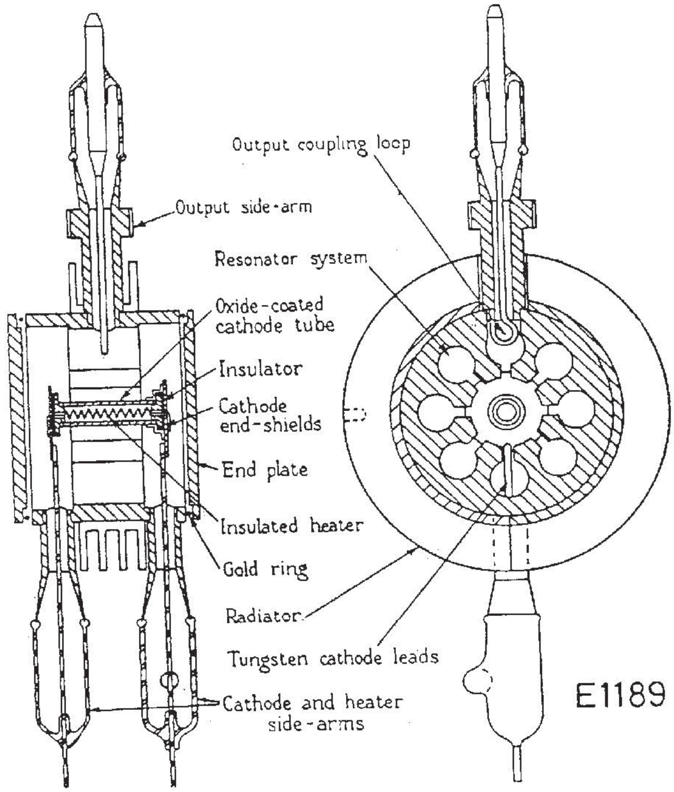


Figure 2. The original schematic of the GEC magnetron, Type 1189.

2. From Invention to Innovation: A Brief Overview of the Complete Magnetron Story

2.1 From Hull's First Idea, to the "Split Anode" Magnetron Used as an RF Source

The story begins in the United States, during the second decade of the 20th century. At that time, radar was nothing but an improbable apparatus of science fiction, and industrial competition was focused on the promising radiotelegraphy. Around 1917, Albert W. Hull (1880-1966) at General Electric proposed in this context to use a magnetic field for controlling the electronic current in a valve, in order to circumvent the famous patent of Lee de Forest's triode. Substituting a magnetic field for an electric field was a quite natural idea, but not without drawbacks. When GE found it was better to buy the triode's patent, the competition was over: the "*magnetron*," the name of which appears for the first time in a paper of 1921 [18], remained no more than a lab curiosity.

In those years, most of the radiotelegraphy applications used the so-called "radio-frequencies," the wavelengths of which were seldom smaller than several hundred meters. Only some pioneers found interest in higher frequencies. In 1920, the German, Heinrich Barkhausen, reached the magical 30 cm (1 GHz) limit with a triode fed in an unusual way, applying the high voltage to the grid instead of to the traditional plate. This Barkhausen oscillator may be seen as the first microwave oscillator, but it seemed clear that it approached the ultimate frequency limits, due to the electron transit time between electrodes into the triode.

The most foresighted researchers turned again their minds to the magnetron. This was suggested – at nearly the same time in 1924 – by the Czech, August Žaček [19-21], who obtained a 29 cm wave with a magnetron used in a sort of Barkhausen configuration; and by the German, Erich Habann [22, 23], who made one step further by producing a kind of "negative resistance" with a cylindrical anode fenced in two parts.

These papers remained unnoticed, and the interest for the "*split anode*" appeared only in the late 1920s in Japan, after Kinjiro Okabe reached with it the wavelength of 12 cm, and, shortly after, of 5.6 cm. This work caused a great stir in the United States when it was published in 1928 in the *IRE Proceedings* [24] by Prof. Hidetsugu Yagi (a former student of Barkhausen). However, after having patented its split anode (Japan, 1927; USA, 1928), Okabe moved his interest towards other subjects. This resulted in a lack of contacts with both Europe and America. At the end of WW II, it was a total surprise to discover that Japanese researchers had pursued the road opened by Okabe during the war, as it will be shown later.

2.2 The Multi-Segment Anode, and the European Studies During the 1930s

After Japan, the scene turns back again to Europe, to three eminent scientists working in industrial laboratories: Maurice Ponte (1902-1983), Figure 3, at SFR-CSF, France; Klaas Posthumus (1902-1990), Figure 4, at Philips National Lab, Netherlands; and Eric C. S. Megaw (1908-1956), Figure 5, at GEC, UK. They significantly improved the performance of the "*split anode*" by multiplying the number of fences to get a "*multi-segment anode*."

Maurice Ponte, a young physicist recruited in 1930 by the French company SFR-CSF [8] to manage its Research Lab, early focused his interest on decimeter waves. He adopted Okabe's principles, with two aims: to clarify the oscillating-mode theory, and to put the magnetron out of the laboratory for field applications:

> ...at the time Japanese magnetrons remained without any practical result, they needed intensive magnetic fields, impractical outside a laboratory. And magnetron theory was still very fragmentary. I started the quest with a theoretical and experimental study of those magnetrons which appeared the simplest to me, i.e. designed with two semi-cylindrical anodes surrounding a cathode filament....

From his first trials, he got 40 W at 100 MHz ($\lambda = 3$ m) with a split-anode diameter of 20 mm, and later on he went to 375 MHz ($\lambda = 80$ cm) with a 5 mm anode diameter. In 1934, he became appointed head of the SFR valve factory, and after having published a complete theoretical analysis of these results [25], he tasked his colleague, Henri Gutton, to go on with the exploration of the anode segmentation.

Klaas Posthumus at Philips (NL) set up in 1933 a split-anode magnetron that delivered about 10 W at 30 cm, and in 1934/5 he successfully developed a four-segment magnetron. However, he is mainly known for his theoretical research. In March 1935, he published in *The Wireless Engineer* a new theory on the magnetron oscillating mode, which he called "*rotating electron cloud theory*" [26]. It showed how the magnetic-field intensity giving the best efficiency could be reduced by the multiplicity of segments. This fact is recognized to have paved the way for the multi-segment developments, and later for the multi-cavity design.

E. C. S. Megaw at GEC (UK) began to study radio propagation at wavelengths below 60 cm nearly at the same time as M. Ponte, and Megaw developed magnetrons for use in his experiments. During this period, he filed six patents on multi-segment anode magnetrons. However, in 1932 he failed in an attempt to make a 12-segment anode work. He became mainly a recognized theoretician, who established his reputation through high-level exchanges with other European scientists, at a time when sharing of knowledge was the common scientific rule. As an example, he made his mark in 1934 in a public debate with K. Posthumus on the magnetron's oscillating modes. This debate,

Figure 3. M. Ponte (CSF, Fr).

Figure 4. K. Posthumus (Philips, NL).

Figure 5. E. C. S. Megaw (GEC, GB).

published in *Nature* [27], was concluded by his agreement with Posthumus's "rotating field theory," which shed new light on the ensuing research.

He also developed contacts with Ponte and his team at CSF, more and more closely spaced over the years, marked by regular visits from one laboratory to the other. The question discussed dealt again with the multi-segment anode: did it work under a new oscillating mode, and was the number of segments limited? The most common opinion (also shared by Posthumus) was that beyond four segments, the tube's efficiency quickly fell. The results shown by Gutton had a major impact on Megaw's understanding of the oscillating mechanisms, and according to Brittain [15], they "were later credited with having exerted a 'profound effect' on British thinking about the cavity magnetron."

These activities, supported by industrial laboratories, give evidence to the interest that radio companies maintained for the magnetron during the 1930s. A statistical analysis of the patents filed in that period [28] confirms it, showing that about 2000 magnetron patents were filed by the major companies between 1920 and 1945. They came mainly from European countries (for a total amount of 861 patents), but the US industry was not so far off, with 727 patents. Many newcomers appeared in the field, such as E. Linder and J. H. Fremlin, followed (in order of productivity) by A. Haeff, C. Hansell, and A. Samuel. Special mention must be made of G. R. Kilgore, who was probably at that time the most important American theorist. In Europe, in addition to the trio previously mentioned, the most-prolific inventor was the German, H. E. Holmann (1899-1960), an independent engineer consultant at Telefunken, later with the firm GEMA, where he contributed to the design of the famous ship-borne radar *Seetakt* [29].

Henri Gutton (1905-1984), who succeeded M. Ponte in 1934, has attached his name to the more-extended study that was made on the segmented anode. Over the ensuing five years, he repeated extensive and systematic experiments on more and more complex anode geometries, with six to eighteen segments of various shapes (see Figure 6). They typically delivered around 10 W on wavelengths varying from 20 cm to 6 cm. Two patents were filed, on April 17, 1937, and December 10, 1937, and a conclusive paper was published in 1938 [30].

In 1938, he made his choice for an anode with eight segments, imbricated and fixed four by four on two opposite metallic discs, according to an architecture named "squirrel cage." As soon as the first trials began, he observed oscillations at some 1.8 GHz, obtained with significantly reduced voltage and magnetic field.

In Figure 6, the "No. 8 tube" is shown, issued from these trials, with a detail of the 2×4 interlaced segments, cooled by the small flanges that can be seen along each segment, and the valve inserted in its permanent magnet. Marketed under the designation "*M-16*," this valve gave 10 W at $\lambda = 16$ cm, with a 15% efficiency, under 765 V for the anode voltage and 430 gauss for the magnetic field.

Figure 6. Gutton's magnetron (M-16 No. 8).

2.3 First Attempts at Application in Early Radars

Most of the work related to the magnetron applications was aimed at directive radio-link applications. However, some early attempts to use them as RF sources for radar can be found as early as 1933, when Rudolf Kühnhold in Germany used a Posthumus 40W/48 cm magnetron in his first trials for naval radar (which led later to the famous Freya [7, 8, 29]). In the same year in the US, William D. Hershberger, an engineer at the Signal Corps Laboratories, built a continuous-wave detection device using a 9 cm RCA magnetron, which he tested in August 1934 on ships entering the New York Bay. In 1936 in Holland, C. H. Staal also used a Philips 10 W/30 cm magnetron for detection trials ordered by the Royal Netherlands Navy [31]. None of these attempts was succeeded by further developments. However, they were indeed on the way to heralding a major innovation coming up.

The most practical application in France was Gutton's project for a "naval obstacle detector," in fact a very early decimetric radar. He submitted his idea to M. Ponte in April 1934, and he patented this equipment on July 20, 1937 [8]. It is worth noting these dates in relation to the famous Watson-Watt memorandum (February 12, 1935). The idea looks like a revival of the Hülsmeyer's Telemobiloskop, of which Gutton had never heard, as usual at that time. Unlike this prior event, his project found an immediate opportunity for exploitation: in January 1935, the owners of the liner "*Normandie*," at that time to be completed, requested that the ship be equipped with the new system. It was mounted onboard very quickly, to have its first trials at sea from mid-1935 [32].

2.4 The Cathode Question

As higher powers were reached, a second point became a major subject discussed between Gutton and Megaw: how to adapt the shape and the structure of the cathode in a multi-segment architecture? Nearly all magnetrons used as a cathode a pure tungsten filament, centered on the anode's axis, and directly heated by the ohmic effect. This fitted well with small tube diameters. However, with the larger diameters of the multi-segment anodes, the result was that the efficiency reduced as the inter-electrode space enlarged. As Megaw explained later, there was therefore a strong relationship between the two points they were discussing [33]:

> ...the restriction of established practice to small cathodes was related to the general conclusion that the use of more than 4 segments was of little practical value; together (these two assumptions) formed a kind of vicious circle which prevented the combination of many segments with large cathodes.

The matter advanced in 1937 when Megaw used a thoriated-tungsten cathode with some success in his E-880, shaped into a spiral to increase its diameter, and he advised Gutton to test it in the *M-16*. This gave nearly 50 W in early 1939, still not enough for the needs of new radar applications. Gutton decided then to insert a cylindrical cathode in his tube, coated with oxide, and indirectly heated by a separate filament. This technique, which was used in classical triodes, proved immediately successful for various reasons: easier cooling, higher resistance to early burning, and better efficiency due to the inter-electrode space reduction. However, the main reason was found later by Megaw: under the condition of so-called "*back bombardment*," the oxide-coated cathode was best able to produce *electron retro-emission*, enhancing the general efficiency of the tube.

A new oxide fitted to *M-16*, giving a peak power of up to 300 W, was shown to Megaw on his last visit in June 1939, and it was decided to provide him with a second sample to be tested at Wembley. This promised exchange was delayed by the outbreak of war, and in the meantime, Gutton still improved his record: in late 1939, a new eight-segment anode and oxide-coated cathode *M-16* delivered a peak-power record of 1 kW at 16 cm.

The last step of the story is quite dramatic. In April 1940, the war situation had become very critical in France. Under this increasing threat, a few days before the German army broke through the front line and rushed to Paris, Dr. Ponte himself crossed the Channel with the admission of the French government, bringing to Wembley two samples of the promised new *M-16* [8]. It was immediately tested by Megaw, and it provided a performance that became decisive in the follow-up.

2.5 Cavities Versus Segments: The Final Step for a Definitive Solution

One can wonder if the success of the multi-segment anode could have been an obstacle that delayed the last and essential evolution towards the cavity anode. In fact, it is now well established that the cavity principle did not appear by miracle on one day of September 1940, in a secret laboratory of the Birmingham University! Conversely, it resulted from a lot of other trials, probably inspired by the cavity klystron of Hansen [34], which cannot be detailed here, but only illustrated by some figures that clearly show the existence of the cavity-anode idea since 1934. They were extracted as examples from patents filed by Arthur Samuel (Bell laboratories, USA, 1934) [35], Hans Eric Hollmann (Telefunken, Germany, 1935) [36], Wilhelm Engberg (Telefunken Germany, 1938), [8, 37], and N. F. Alekseev and D. D. Malairov (USSR, 1937) [38] (see Figure 7).

Special attention must be paid to the Russian work conducted in 1936-37 at the University of Leningrad by N. F. Alekseev and D. D. Malairov. With four cavities, their experimental device gave 300 W at 9 cm. However, it was unable to go further without burning the cathode, a question they had not solved.

The cavity design of their experimental setup seems very close to the Engberg design. This has been cleared by Sir Bernard Lovell, a H2S's father, who discovered in 2001 a German report from his colleague, Otto Hachenberg, dated May 1943. It revealed that the principle of the cavity magnetron was already well known at Telefunken, based on work published in Leningrad in 1936! This made Sir Lovell [11] wonder if, "was the secret necessary?"

In Japan, research was also carried out following the early studies of Okabe, even though, in contrast to the previous publications, the work was conducted under strict military discretion, and therefore could not be known in Europe before the war.

In 1938, the Navy officer Yoji Ito (a former student of Barkhausen), and his younger brother, Shigeru Nakajima, produced a first eight-segment magnetron named Tachibana ("Mandarin"), which gave 30 W at 6 cm, or 1 W at 1.5 cm [39]. When looking closely at its anode's shape, one can see segments connected pair-wise by a metallic strip shaped as a triangular cylinder, which appeared as an early step towards the cavity scheme. In the following realizations, this design evolved into a copper block with radiating cuts, the shape of which is clearly referred to by the names of the new devices: "plum flower," "gentian," "chrysanthemum," and also a splendid "cosmos – rising sun" including 24 cavities. In April 1939, Nakajima issued from these attempts an eight-cavity "*M3*" giving 500 W at 10 cm, nearly one year ahead of the British E-1188. Years after the war, in April 1953, Nakajima discovered this E-1188 at the London Science Museum with great surprise [39, 40]:

> After the war, I had an opportunity to visit the Science Museum of London, in April 1953, and I was very much surprised to see the cavity magnetron invented in 1940 by Birmingham University...on examining this magnetron, the dimensions of glass covering the vacuum, the water-cooling system around the anode, and the anode mechanism, I was struck by the similarity with ours. At first, I could not distinguish it from the water-cooled magnetron we developed!

and finally,

> This is a good example of an old Japanese proverb, which says that 'there is no difference in brain intelligence between the East and the West'....

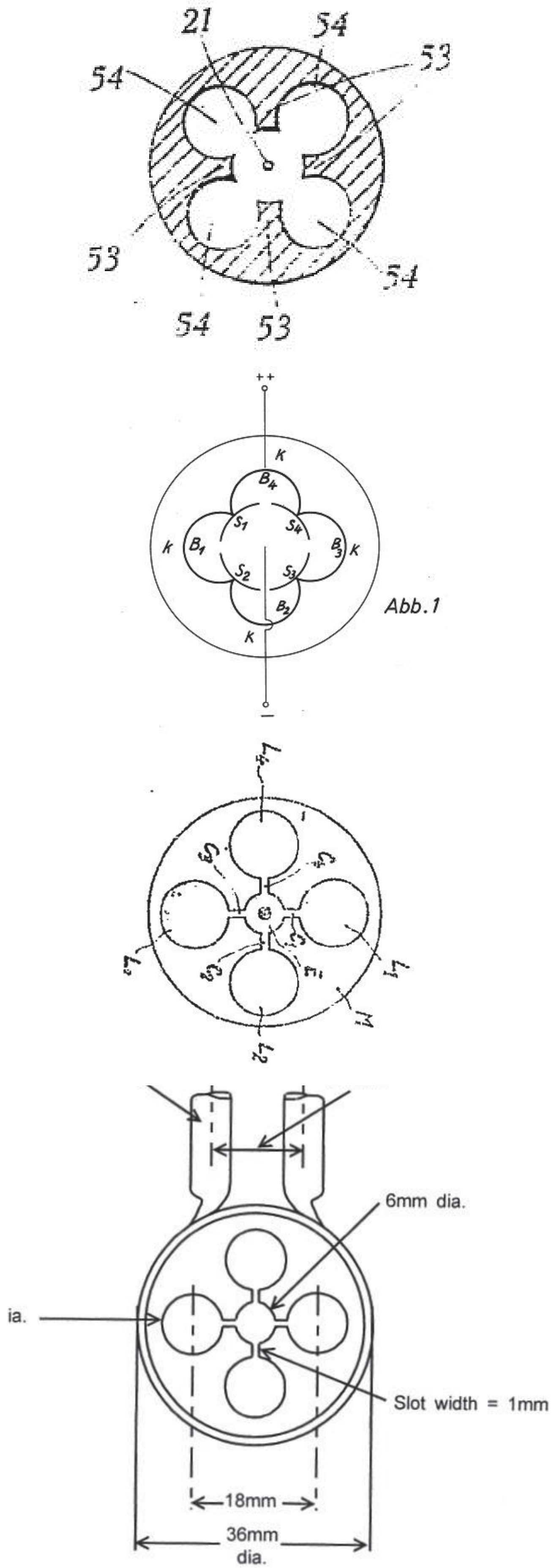


Figure 7. Early cavity magnetron architectures.

2.6 The Birmingham Magnetron Paves the Way to High Power Sources and Microwave Radar

On September 1939, the cavity magnetron was thus already a confirmed concept, well known in USSR, Germany, and Japan...but not at Birmingham, where Randall and Boot were totally unaware of it. In his long augmented biography of Randall, M. H. F. Wilkins refutes any polemic about that [10]. Indeed, knowing where they found their inspiration does not really matter: the credit to them is that they aimed at a specific objective (as simply expressed by Prof. M. Oliphant, "a microwave source giving one kilowatt on a ten centimeters wavelength") to satisfy an urgent need (a centimetric airborne radar that would save the Londoners from the daily fright of the Blitz), and that, in a very short time, they gave to this demand a right and very efficient solution.

The first test of the cavity anode of Randall and Boot proved immediately to be very promising. On February 21, 1940, a six-cavity prototype gave 400 W at 9.9 cm, with an estimated efficiency between 10% and 15%, nearly half of their specified objective, and close to the previous results obtained by Megaw and Gutton after more than five years of continuous improvements. Absolute secrecy was immediately compelled on their work, and shared with the GEC team, which was asked to develop a true industrial device based on the Birmingham prototype (see Figure 8).

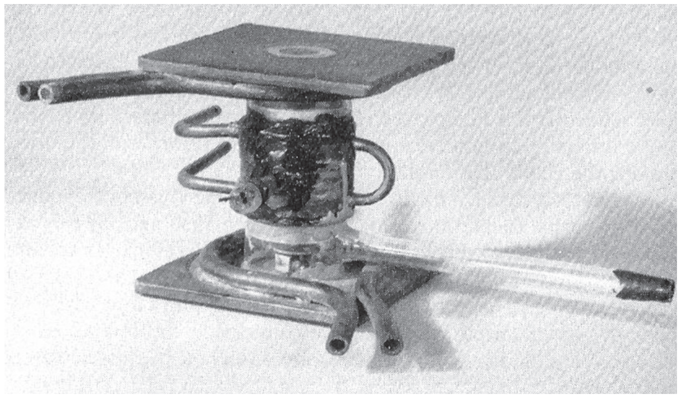


Figure 8. The Randall-Boot first prototype.

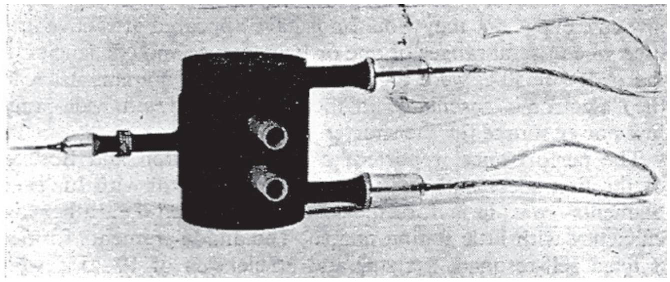


Figure 9. Magnetron Type E-1188 (GEC, May 16).

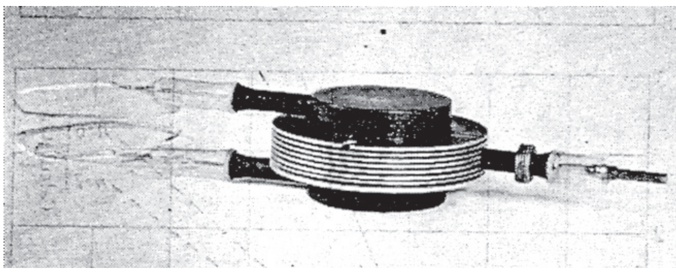


Figure 10. Magnetron E-1189 serial No. 1 (GEC, June 29).

The last step was still to be made. It is worth underlining the decisive part played there by E. C. S. Megaw, as the final architect of a device that had to become a major innovation of the radar story. The role he had played for more than ten years as organizer of scientific European exchanges, enforced by his own experience, and combined with a deep knowledge of the military requirements originating from his position in GEC, had put him in the best situation to set up the cornerstone of the magnetron edifice. The task was led very quickly to its successful completion.

The prototype of Randall and Boot used waxed seals, as facilities to manufacture sealed-off tubes were not available in Birmingham, and it was operated in a continuous-wave mode. After being introduced to the secret in April 1940, Megaw understood and immediately planned an improved six-cavity model with a sealed-off vacuum housing, an electromagnet weighting less than 50 pounds, and a working pulse mode. This E-1188 (Figure 9) was completed on May 16, giving a performance similar to that of the Birmingham model. It was quickly followed by a new E-1189 (serial No. 1: Figure 10), designed on May 25 for use in an AI airborne radar. This combined a compact sealed-off all-metal and air-cooled housing, a reduced axial dimension allowing the use of a minimum air gap for the magnet, and an enlarged thoriated-tungsten spiral cathode. First operated on June 29, it gave an output of 3 kW with a 1000 oersted permanent magnet. However, when it was challenged for higher 5 kW to 10 kW power, it still suffered from a reduced lifespan, due to a fast evaporation of the directly heated spiral filament.

We know that the question had been solved by H. Gutton with the oxide-coated cathode used for the *M-16*, and revealed at Wembley by Dr. Ponte himself on May 6. As explained later by Megaw, the result was due mainly to the secondary electron back-bombardment, which made the power output almost independent of the heater voltage. During his visit, Ponte was kept away from the cavity secret, but he left to Megaw very valuable information that arrived just in time to be incorporated into a new device. In the E-1189 (serial No. 2), an oxide-coated cylinder with a 0.45 cm diameter took the place of the spiral filament. This turned out to be the decisive improvement: bringing together the principles of the cavity anode and the oxide-coated cathode, the E-1189-b tested on June 26 gave a still-increased peak power of 15 kW, with a satisfying lifespan, which exceeded all expectations.

When this E-1189 was disclosed to the US allies in September 1940 by the Tizard mission, it is fair to say that American experts were stupefied by its performance. Immediately integrated in the gigantic war effort of the US industry, the cavity magnetron became the heart of more than 150 new radars of all categories designed between 1941 and 1944. This gave to the allied armies a decisive advantage, which changed the course of WWII.

3. Concluding Remarks

Like many other disruptive breakthroughs, the cavity magnetron was the result of a number of related explorations, in technology, in experiment, and in theory. Many other scientists, scattered over quite a few countries, made significant advances. However, exchange of ideas and opinions in scientific forums was getting more and more difficult in the build-up for WW II, as well as between Eastern and Western scientists in the ensuing "Cold War" period. The actual global status of science and technology was known in a rather fragmented way to many engineers and scientists. The military relevance at the time led to teams working on the same type of problem, but in imposed isolation. Although the Birmingham team had brilliant ideas and their share in the development proved decisive, it is fair to say that without the contributions from others, their degree of success and the pace of the progress would not have been so great, or maybe it would have been too late for a timely development of microwave high-power radar in World War II.

4. References

1. E. G. Bowen, *Radar Days*, Briston, UK, Adam Hilger (Institute of Physics Publishing), 1987.

2. L. W. Alvarez, *Adventures of a Physicist*, New York, Basic Books, 1987.

3. B. Lovell, *Echoes of War*, Bristol, Adam Hilger, 1991.

4. D. E. Fisher, *A Summer Bright and Terrible: Winston Churchill, Lord Dowding, Radar, and the Impossible Triumph of the Battle of Britain*, Berkeley, CA, Counterpoint Press, 2005.

5. D. Zimmermann, *Top Secret Exchange: the Tizard Mission and the Scientific War*, Montreal, McGill Queen's University Press, 1996.

6. P. A. Redhead, "The Invention of the Cavity Magnetron and its Introduction Into Canada and the U.S.A.," *La Physique au Canada*, Novembre-Décembre 2001, pp. 321-328, linked as "Complement F" of [7].

7. G. Galati, *Cent'anni di radar – Ricerca, sviluppi, persone, eventi* [One Hundred Years of Radar – Research, Developments, Persons, Events], Rome, Aracne Editrice, 2012 (in Italian).

8. Y. Blanchard, *Le radar, 1904-2004: histoire d'un siècle d'innovations techniques et opérationnelles* [The Radar 1904 – 2004: History of One Century of Technical and Operational Innovations], Paris, Ellipses, 2004 (in French).

9. R. C. Watson, Jr., *Radar Origins Worldwide*, Bloomington, IN, Trafford Publishing, 2009.

10. M. H. F. Wilkins, "John Turton Randall (23 March 1905 – 16 June 1984)," *Biographical Memoirs of Fellows of the Royal Society*, **33**, 1987, pp. 493-535.

11. B. Lovell, "The Cavity Magnetron in World War II: Was the Secrecy Justified?," *Notes and Records of the Royal Society of London*, **58**, 3, 2004, pp. 283-294.

12. S. Phelps, *The Tizard Mission: The Top Secret Operation that Changed the Course of World War II*, Yardley, PA, Westholme Publishing, 2010.

13. Proceedings of the International Conference CAVMAG 2010 on 70 years of Cavity Magnetron, Bournemouth University, U.K., 19-20 April 2010, available online: http://academic.research.microsoft.com/Conference/4631/cavmag-international-conference-on-the-origins-and-evolution-of-the-cavity-magnetron, http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=5557902.

14. R. L. Wathen, "Genesis of a Generator – The Early History of the Magnetron," *Journal of the Franklin Institute*, **255**, 4, 1953, pp. 271-287.

15. J. E. Brittain, "The Magnetron and the Beginnings of the Microwave Age," *Physics Today*, **38**, 1985, pp. 60-67.

16. H. E. Guerlac, "The Early History of Microwaves," in *Radar in World War II*, The History of Modern Physics 1800-1950 series, American Institute of Physics, New York, Tomash Publishers, 1987, Chapter 8, pp. 185-240.

17. E. B. Callick, *Meters to Microwaves, British Development of Active Components for Radar Systems, 1937 to 1944*, IEE History of Technology series 11, Stevenage, UK, Peter Pelegrinus Ltd., 1990.

18. A. W. Hull, "The Effect of a Uniform Magnetic Field on the Motion of Electrons Between Coaxial Cylinders," *Physical Review*, **18**, 1, 1921, pp. 31-57 .

19. A. Žáček – "Magnetron Generators," *Slaboproudy obzor* [*Journal of Czechoslovak Radio Engineers*], **1**, 1, pp. 6-9 and 1, 2, pp. 22-26, 1936 (in Czech).

20. A. Žáček – "Nová metoda k vytvorení netlumenych oscilací [New Method of Generating Undamped Oscillations]," *Časopis pro pěstování matematiky a fysiky* [*Journal for the Cultivation of Mathematics and Physics*], **53**, 1924, pp. 378-380 (in Czech).

21. L. Mergl – "Magnetron – Its Origin and the Contribution of August Žáček to its Development," in *DVT dejiny ved a techniky* [*History of Sciences and Technology*], **XXXI**, Prague, Society for the History of Sciences and Technology, 1998.

22. E. Habann, "Eine neue Generatorröhre [A New Generator Tube]" *Zeitschrift für Hochfrequenztechnik*, **24**, 1924, pp. 115-120 and 135-141 (in German).

23. E. Habann, *Die neuere Entwicklung der Hochfrequenztelephonie und telegraphie auf Leitungen [Recent Developments of Wired High Frequency Telephony and Telegraphy]*, Braunschweig, Germany, Vieweg & Sohn, 1929.

24. H. Yagi, "Beam Transmission of Ultra Short Waves," *Proceedings of the IRE*, **16**, 6, 1928, pp. 715- 740.

[25. M. Ponte, "*Sur l'emploi des champs magnétiques pour la production des ondes ultra-courtes* [On the Usage of Magnetic Fields in Microwave Generation]," in *Vingt-cinq années de T.S.F.* [*Twenty-Five Years of T.S.F.*], Paris, SFR ed. Makowsky, 1935, pp. 183-198.

26. K. Posthumus, "Oscillations in a Split Anode Magnetron," *The Wireless Engineer*, **12**, 1935, pp. 126-132.

27. K. Postumus and E. C. S. Megaw, "Magnetron Oscillations," *Nature*, **135**, 3422, 1935, pp. 914-914.

28. M. Leconte, "Statistical Study of Magnetron Patents in the Early Year of Electronics Between 1920 and 1945," Proceedings of CAVMAG 2010, International Conference on the Origins and Evolution of the Cavity Magnetron, Bournemouth, UK, April 19-20, 2010, pp. 11-16.

29. F. Trenkle "Die deutschen Funkmessverfahren bis 1945 [The German Radio Measurement Techniques Until 1945]," Huthing, DE, 1986.

30. H. Gutton and S. Berline, "Research on the Magnetrons: S.F.R. Ultra Short Waves Magnetrons," *Bulletin de la Société Française Radio-Electrique*, 12ème année, **2**, 1938, pp. 30-46.

31. F. O. J. Bremer and P. van Genderen (eds.), *Radar Developments in the Netherlands*, Thales Hengelo, NL, 2004.

32. Elie, Henri Gutton, Hugon, Ponte, "Détection d'obstacles à la navigation sans visibilité [Detection of obstacles in blind navigation]," *Bulletin de la Société Française des Electriciens*, 5ème série tome **IX**, 100, 1939, pp. 345-353.

33. E. C. S. Megaw, "The High-Power Pulsed Magnetron: A Review of Early Developments," *Journal of IEE*, **93**, 5, part III A, 1946, pp. 977-984.

34. W. W. Hansen, *High Efficiency Resonant Circuit*, US Patent No. 2,190,712 (applied July 27, 1936; granted February 20, 1940).

35. A. Samuel *Electron Discharge Device*, US Patent No. US2063342A (applied December 8, 1934; granted December 8, 1936).

36. H. E. Hollmann, *Magnetron*, US Patent No. US2123728A (applied November 29, 1935; granted July 12, 1938).

37. W. Engberg, "Schlitzanodenmagnetronroehre fuer ultrakurze Wellen [Slot anode magnetron tube for ultra short waves]" German Patent No. 938 196 (applied November 14, 1938; published in France on July 1, 1943, and in Germany on January 1, 1956).

38. N. F. Alekseev and D. D. Malairov, "Generation of High-Power Oscillations with Magnetron in the Centimetric Band," *Proceedings of the IRE*, **32**, 3, March 1944, pp. 136-139.

39. S. Nakajima, "The History of Japanese Radar Development to 1945," *Proc. of IEE 85 - Seminar on the History of Radar IEE 85*, 10-12 June 1985, London, UK, edited by IEE - London, Peter Pelegrinus Ltd., London, 1988, Chapter 18, pp. 243-258.

40. S. Nakajima "Shigeru Nnakajima, An Interview Conducted by William Aspray (May 26, 1994)," Part of the Japanese Oral Histories Collection, Center for the History of Electrical Engineering, IEEE and The State University of New Jersey, 1994.

Introducing the Authors

Yves Blanchard was born in 1942, is a consulting engineer. He graduated from ISEN Lille in 1966. He has been a research engineer in sonar and radar for 25 years, first with the French National Centre for Aerospace Studies and Research (ONERA), and later in industry with Thales, where he ended as Technical Director of the Missile Electronic unit of Thales Airborne Systems. He is also a well-known researcher into the history of radar, and has given nearly 40 papers and conferences on the subject. He is the author of a general history of radar developments, acknowledged in France as a referring book: *Le Radar 1904-2004, Histoire d'un Siècle d'Innovations Techniques et Opérationnelles* [The Radar 1904-2004: History of One Century of Technical and Operational Innovations] (Paris, Ellipses ed., 2004).

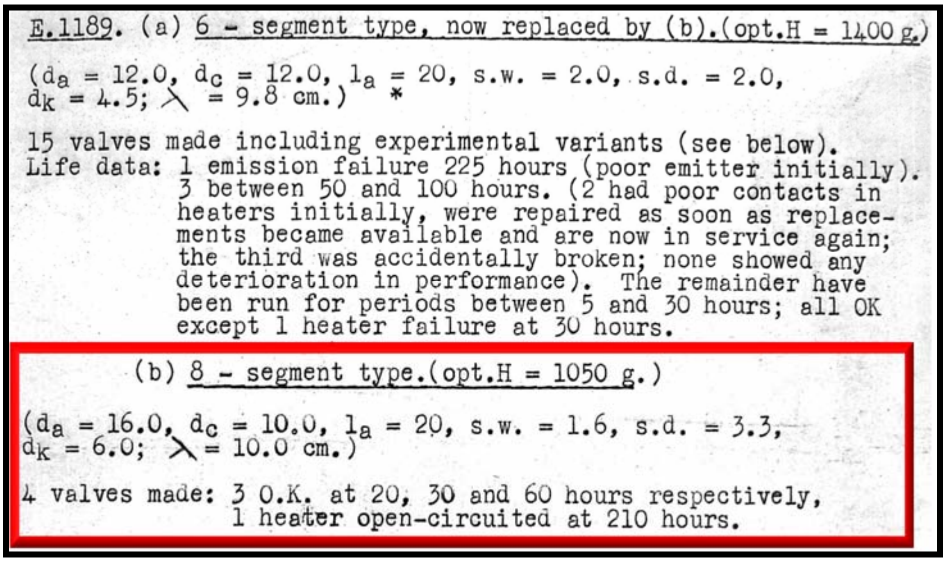
Gaspare Galati was born in 1946. He has been an active researcher in radar systems since the early 1970s. He started with the company Selenia, where from 1984 to 1986 he headed the System Analysis Group of the Research Department. Presently, he is a full professor of Radiolocation at the Tor Vergata University of Rome, where he also teaches probability, statistics, and random processes. His main interests are in radar theory and techniques, detection and estimation, navigation and air traffic management, and recently, the history of Italian radar. This is treated in his book *Cent'anni di Radar – Ricerca, Sviluppi, Persone, Eventi* [One Hundred Years Of Radar – Research, Developments, Persons, Events]," (Rome, Aracne Editrice, 2012).

Piet Van Genderen was born in 1947. He graduated from the University of Twente in Enschede in 1971. He worked with the National Aerospace Laboratory in Amsterdam until 1979. He then moved to Hollandse Signaalapparaten, now Thales Nederland, where he held several positions in R&D. In 1994, he was also appointed a full professor at the Delft University of Technology. He holds an honorary doctorate of the MTA of Bucharest, Romania. His main research interests are in the design of waveforms and associated algorithms for extracting object features. He is editor of the book *Radar Developments in The Netherlands* (2004).

E.1189 C 328 8-Cavity Magnetron Prototype, July 1940

This sample is, to the best of our knowledge, the very first prototype of the E1189 eight-cavity magnetron design. Probably it started oscillating in the GEC laboratories within the end of July 1940, while the E1189 No.12, the one brought to America by the Tizard Mission, was in progress to be assembled.

It has small characters punched on the copper cylinder, 1189 C 328. No doubt that the first four digits stay for the design code E1189. This was the GEC internal code for the first 10 cm multi-cavity magnetron, appeared in the mid 1940. ‘C’ could indicate the third revision, assuming that ‘A’ was the six-cavity design No.1, the one with filamentary cathode, and ‘B’ was the E1189 No.2, the six-cavity one with oxide-coated unipotential cathode. In the last group of digits, ‘32’ could indicate the anode height and ‘8’ could refer to the number of cavities. Dimensions of the body and of every details, as holes, slots and cathode, are all compatible with those given by Megaw for the eight-segment E1189 itself **(*7)**.



E.1189. (a) 6 - segment type, now replaced by (b).(opt.H = 1400 g.)

(d_a = 12.0, d_c = 12.0, l_a = 20, s.w. = 2.0, s.d. = 2.0,
d_k = 4.5; λ = 9.8 cm.) *

15 valves made including experimental variants (see below).
Life data: 1 emission failure 225 hours (poor emitter initially).
3 between 50 and 100 hours. (2 had poor contacts in heaters initially, were repaired as soon as replacements became available and are now in service again; the third was accidentally broken; none showed any deterioration in performance). The remainder have been run for periods between 5 and 30 hours; all OK except 1 heater failure at 30 hours.

(b) 8 - segment type.(opt.H = 1050 g.)

(d_a = 16.0, d_c = 10.0, l_a = 20, s.w. = 1.6, s.d. = 3.3,
d_k = 6.0; λ = 10.0 cm.)

4 valves made: 3 O.K. at 20, 30 and 60 hours respectively,
1 heater open-circuited at 210 hours.

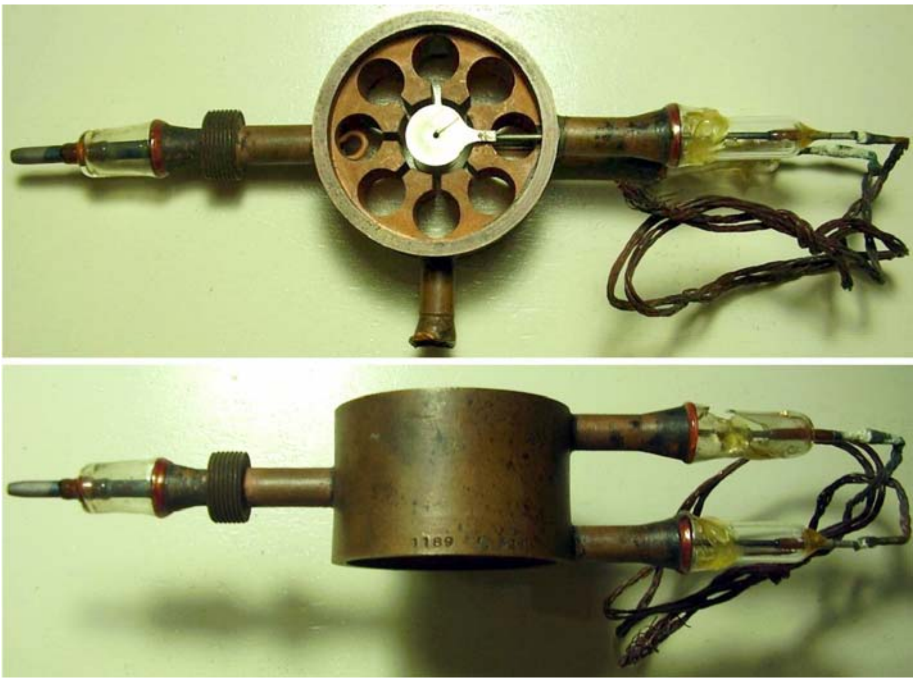
The anode block looks made of bare copper, no radiating fins were brazed to its outer wall. It is a cylinder measuring 50 mm diameter by 32 mm overall height. A partially erased hand inscription containing characters ‘??75/HR210’ is still visible on the body, near to the heater spacers. The block has eight hole-and-slot resonating cavities all around its axis. Other measures are similar to those given for the E.1189 eight-cavity type: 20 mm anode useful length, 16 mm anode internal diameter, 1.6 mm slot width, 3.3 mm slot aperture. Inside one of the two end spaces, the wall around the cathode rod still shows traces of a clear and sticky substance, probably sealing grease.

A large center hole accommodates the 10 mm diameter oxide-coated cathode assembly, held by two rods going to the outside through a couple of glass stems and welded to the flexible heater-cathode stranded wires. The heater helix ends terminate to a couple of baffles, welded to the heater rods. The baffle corresponding to the common heater/cathode connection is spot welded to the flanged cathode cylinder. The oxide layer appears uniform over about two-third of the surface. A relevant thinning of the oxide can be observed near the two ends of the cathode cylinder, leaving the nickel exposed in a couple of zones. Near to the cathode floating end, the oxide layer is visibly swollen and even detached in a small zone.

A small copper tube, about 20 mm long and flared to the external edge, is brazed on the outside of anode block, halfway between its ends and orthogonally to the cathode/heater supporting rods. The tube shape recalls that of the heater spacers. Almost certainly a glass stem was sealed to it. Probably it was intended to evacuate the anode chamber while continuously pumping and at the same time making it possible to observe the cathode temperature by pyrometric techniques.

By no way this sample can be confused with the quite common display units obtained removing the end caps from standard magnetrons, to show their internal construction. None of the known magnetrons looks like this one. The code punched on the copper block, the absence of both the end covers and of any radiator and especially the presence of the side copper tube suggest that this sample was a very early developmental prototype of the GEC eight-cavity E.1189 magnetron design. The cathode/heater subassembly is complete and the oxide layer shows clear signs of rough operations, even beyond safe limits. The bubble in the oxide might indicate local arcing. Traces of clear sealing wax reinforce the possibility that it was used in a test rig while continuously pumped, almost certainly closed by movable end plates, into the pole pieces of a permanent magnet.

For sure this prototype was built to be powered and actually it was, to the point of damaging the oxide layer on the cathode. No need for the complete cathode subassembly, including oxide, heater and end baffles, if it was intended as a nice paperweight. Its manufacture looks too accurate to believe that it could be built in handicraft laboratory, such as that of the Birmingham University could be. Everything leads us to assume that it was built at GEC for internal test purpose.



Two more views of the sample, with the code punched on the outside of the anode block.

- Left, the barely visible handwriting on the anode block, containing the characters '/HR210'. Not sure but the first part of the writing might contain '75', indicating that the tube was operated for 75 hours before the endurance test. Right, the heater wire is broken at the welding to the floating end baffle, opposite to the one welded to the cathode cylinder.

- Two views of the cathode surface. The oxide layer is uniform and in good shape for about four-fifths of the cathode cylinder. Near one of the ends the layer is quite thin somewhere, leaving exposed the underlying metal. Oxide also looks swollen and detached in the small area evidenced in the image at right. One side of the cylinder ends in a flange, spot welded to the one end baffle. Not sure, but metal looks to be nickel..

- Detailed view of the internal hole corresponding to the side copper tube. It is round and exactly in the middle of the resonator. By the way, looking from outside through the copper tube, the visible cathode surface appears in a good shape. Unfortunately in the second image the oxide surface is out of focus and just its uniform whitish look can be appreciated. On the right, the hole hosting the output coupling loop looks to have the same diameter.

Dating the sample

From April, GEC began to work side by side with Birmingham at the development of the cavity magnetron just devised. We know from the paper ‘The Cavity Magnetron’ by Boot and Randall (*13) that several steps of development were already planned at the date. We have the full list of developmental cavity magnetrons with different resonator systems built at GEC up to the date of 11 October 1940 in a **Megaw’s secret report** **(*7)**. Megaw lists four units made of eight-segment, 1.050 gauss E1189. We know from the 1946 Megaw’s notes **(*8)** that two of these units were serialized as No.12 - the one brought to America by Bowen - and No.13, used by Megaw himself to characterize the new device. The four units operated for different numbers of hours: this leads us to assume that they were put into operation as soon as they were ready and then that they were all turned off at the same time. Only one of them, the first one to be operated, was later put back into operation for the endurance test, until the heater became open-circuited. The main development steps of the eight-cavity magnetron are also fixed by another source, the wartime diary of Sir Clifford Paterson, Director of the GEC Research Laboratories at Wembley.

Almost certainly our sample is the fourth E.1189 type b, listed by Megaw, the one totalizing 210 hours until heater opened. Few doubts that it was built and first operated while still assembling the sample eventually given to Bowen. It was first used to perform functional tests on the new eight-cavity design and after August 7 it was used to perform an endurance test.

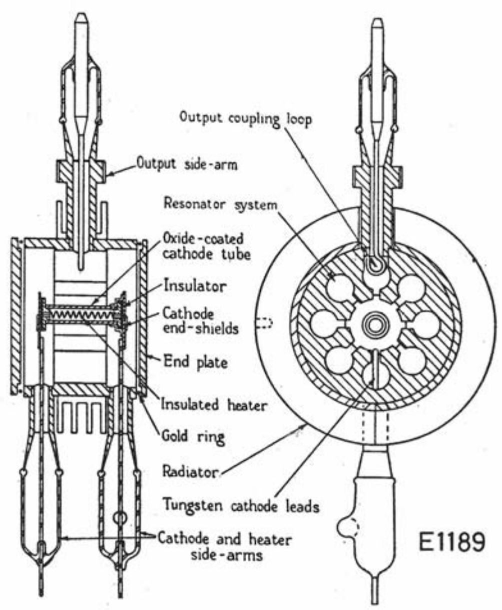
To confirm the above reconstruction, here is the page visible in the old GEC Archives, which represents the second Prototype 1189 C 328 of eight-cavity magnetron ever built.

Here is the summary of its main features:

- The design and the same dimensions of electrodes are identical to those of the final release of E.1189.
- It is complete with an oxide-coated cathode subassembly which shows clear traces of operation. The heater wire is broken at one end. Traces of vacuum grease are still visible inside the copper block, near to one of the edges.
- The absence of the external finned radiator, the presence of a copper short tube and the lack of end caps clearly indicate that it was an experimental unit, made for internal laboratory tests at GEC and operated while continuously pumped.
- On the copper anode block a punched code starts with the characters '1189', followed by C 328. 'C' could stay for the revision level of E.1189, after the six-slot filamentary cathode and the six-slot oxide-coated cathode designs.
- On the same block, handwritten with a marker, '??75/HR210' characters can be read, that could be the running hours at 6 August and the total life of the fourth sample listed by Megaw. 75 could stay for the hours worked until 6 August.
- The source of this sample was the same of several other historical tubes, related to the developments of British radar. Possibly coming from a British Marconi warehouse.
- The No.2 prototype advertised in this page by GEC looks identical.

No doubt then that this E.1189 prototype is the very early eight-cavity magnetron sample operated at GEC in performance tests. Probably it started oscillating since the end of July, while the sample No. 12 - the one brought to America by the Tizard Mission - was still in progress of being assembled. Later, after the approval of the eight-cavity design review on 6 August, it was used to run an endurance test, until heater opened after 210 hours of operation.

The reconstruction of the eight-cavity magnetron development at GEC can be read at this link.



Final draft of E.1189 magnetron approved as NT89 (A.P. W.2510) or REL 3D. The finned radiator is simpler than the one in the No.12 sample, with four fins instead of eight. Click to enlarge.

Acknowledgements

My thanks go to the many people which supplied information useful to reconstruct the development of multi-cavity magnetron at Birmingham and at G.E.C. A special thanks goes to Mr. Yves Blanchard who sent this **kind mail** with his authoritative opinion and some documents that I added to the references below.

References and bibliography:

1) **Callick E.B. - Metres to Microwaves**
2) **G.B. Collins - Microwave Magnetrons**
3) **Sir Bernard Lovell - Echoes of war**
4) **E.G. Bowen - Radar Days**
5) **Paul A. Redhead - The invention of cavity magnetron and its introduction into Canada and the U.S.A.**
6) **Y. Blanchard, G. Galati, P. van Genderen - The cavity magnetron: not just a British invention**
7) **E. Megaw - Notes on magnetron development programme**
8) **E. Megaw - The high-power pulsed magnetron: a review of early developments. February 1946**
9) **R. Clayton & J. Algar - The GEC Research Laboratories 1919 - 1984**
10) **M.J. LAZARUS - "Electromagnetic radiation : Megahertz to Gigahertz. A tribute to Heinrich Hertz and John Turton Randall", Proceedings IEE, Vol. 133, part A, n°2 (march 1986), pp. 109-118**
11) **W.E. WILLSHAW – « GEC's Wartime contribution », in "Fifty years of the Cavity Magnetron", Proceedings of a " One-day symposium " (21 february 1990), pp. 61-70, ed. by P.M. Rolph, The School of Physics and Space Research, University of Birmingham (1991)**
12) **W.E. WILLSHAW – « Microwave magnetrons : a brief history of research and development », GEC Journal of Research, vol.3 (1985), pp. 84-91**
13) **H.A.H. BOOT et J.T. RANDALL - " The cavity magnetron ", Journal of IEE, vol 93, part III A, n° 5 (1946), pp. 928-938**
14) **Otto J. Scott - The creative ordeal: The story of Raytheon**
15) **Sir Clifford Paterson - A scientist's war.**
16) **Stephen Phelps - The Tizard Mission**
17) **Emilio Ciardiello, ASE - The development of eight-cavity E1198 at GEC**

Last edited on June 2, 2020 by Emilio Ciardiello

Megaw secret report, 1940

SECRET.

Not for circulation.

RESEARCH LABORATORIES OF THE GENERAL ELECTRIC COMPANY, LTD.

11th October, 1940.

Notes on Magnetron development programme (I).

E.Megaw.

1. Data on standard types.

E.1189. (a) 6 - segment type, now replaced by (b).(opt.H = 1400 g.)

(d_a = 12.0, d_c = 12.0, l_a = 20, s.w. = 2.0, s.d. = 2.0, d_k = 4.5; λ = 9.8 cm.) *

15 valves made including experimental variants (see below).
Life data: 1 emission failure 225 hours (poor emitter initially). 3 between 50 and 100 hours. (2 had poor contacts in heaters initially, were repaired as soon as replacements became available and are now in service again; the third was accidentally broken; none showed any deterioration in performance). The remainder have been run for periods between 5 and 30 hours; all OK except 1 heater failure at 30 hours.

(b) 8 - segment type.(opt.H = 1050 g.)

(d_a = 16.0, d_c = 10.0, l_a = 20, s.w. = 1.6, s.d. = 3.3, d_k = 6.0; λ = 10.0 cm.)

4 valves made: 3 O.K. at 20, 30 and 60 hours respectively, 1 heater open-circuited at 210 hours.

E.1198.

(p = 4, d_a = 16.0, d_c = 10.0, l_a = 20, s.w. = 2.0, s.d. = 3.05, d_k = 6.0; λ = 9.1 cm.; opt.H = 1150 g.)

4 valves made: 3 O.K. at 25, 10 and 4 hours; 1 accidentally broken at 85 hours then repaired; now O.K. at 75 hours.
3 further samples are approaching completion for A.M.R.E.

The general position on life and stability of performance appears to be satisfactory, though heater failures have been too numerous. It has been found that the insulating coating on the heater spirals has not been up to normal standards and this is being attended to. Life test gear will shortly be available for continuous operation, independent of the experimental programme. A total of 35 valves (including repairs) has been made with the gold seal technique without a failure of the seal.

2. /

* Symbols used:
p = no.of pairs of segments,
d_a = anode diameter,
d_c = circuit hole diameter,
l_a = anode length,
s.w. = slot width,
s.d. = slot depth,
d_k = cathode diameter,
H = magnetic field strength,
E_a = anode voltage,
I_a = anode current,
λ = wavelength; dimensions in mm.

2. Valves for shorter wavelengths.

(a) E.1218. (aimed at 7.5 cm.)

($p = 5$, $d_a = 16.0$, $d_c = 8.0$, $l_a = 20$, s.w. = 1.6, s.d. = 2.8, $d_k = 6.0$; $\lambda = 7.9$ cm.; opt. H = 1120g.).

2 valves made: both O.K. at a few hours. (1 sent to A.M.R.E.) On oscillation test at 9 kV. 6A. peak input, H = 1100 g., the output was of the same order as for E.1198 (accurate measurements not yet made but the efficiency is certainly of the order of 10%).

If further valves are required the wavelength will be adjusted to 7.5 cm. or whatever exact figure is decided on in that neighbourhood.

It is satisfactory to note that the wavelength range of 12 to under 8 cm. has now been covered without any indication of reduction of efficiency with decreasing wavelength.

(b) Study at about 10 cm.of constructions adapted to shorter wavelengths.

(i) Coupling methods.

Variations from the central coupling loop are being tried out in C.W.designs (q.v.below). The first of these, coupling loop of the same size placed just outside the end of one circuit hole, has given approximately the same output and efficiency though the coupling coefficient was considerably reduced. Coupling and tuning conditions (on the coupling line) are more critical and this made it appear on a first trial that the available output was less.

The second variation, which would probably be the most convenient for the shortest wavelengths, namely direct tapping of the inner of the coupling line on one of the resonent elements, is included in a valve now being made. The analogue of this in a glass receiving magnetron (E.1210) with resonant strip segments is being used with complete success at about 10 cm.

(ii) Form of resonant cavities.

The "hole and slot" construction has been extended in the direction of deeper slots to the point at which the slot depth is about equal to the hole diameter without any difficulties arising. Two C.W. valves are now in hand with resonent elements formed by radial blades ("commutator valve"), one valve with a central coupling loop and one with the direct tap referred to above. The important dimensions are the same as those of the C.W. valves already made.

It will be clear that the aim in all this has been to avoid indefinite conclusions by making only one change at a time.

(iii) Effect of increasing p.

Valves have now been made with p = 2,3,4,5 and 6. There is some indication of an improvement in efficiency between p = 2 and p = 4 and there appears to be little change between p = 4 and p = 6, though in the last case there is some evidence that the efficiency curve against H has two peaks just below and just above the calculated opt.H. This may

may perhaps be a function of the ratio of slot width to segment width rather than of p; further trials are required to clear this up and will be made in due course. It appears that the width ratio (slot/segment) is otherwise not a critical variable at least for values between about 0.2 and 0.4.

(c) Valves with structure similar to E.1198 for shorter wavelengths.

A design for λ = 4.5 cm., pulse operation, is being made to which the following data apply:-

λ=4.4 (measured) p = 8, d_a = 16.0, d_c = 4.0, l_a = 20, s.w. = 1.0, s.d. = 2.7, d_k = 6.0; opt.H = 1150g., opt.E_a = 9 kV.; central coupling loop.

The difficulties of proceeding farther in this direction are purely geometrical; as p is increased with decreasing λ to keep opt.H constant, d_c has to be reduced by a factor greater than that by which p is increased, so that the tendency is towards small circuit holes with deep slots and mechanical problems arise in the coupling loop design. Hence the desire to change the form of the coupling and of the resonant cavities. These difficulties are increased in C.W. designs where even greater values of p are necessary to give a reasonably low anode voltage without excessively small anode diameter.

The design detailed above certainly does not represent the limit, but it is proposed to complete the exploratory experiments at about 10 cm. before attempting what may prove to be an unnecessarily difficult construction for still shorter wavelengths

If the "commutator valve" with direct coupling does succeed at 10 cm.(the disappointing though perhaps inconclusive results of the first Birmingham experiments show that its success is not a foregone conclusion), and there is as little variation of efficiency with p in going from p = 6 to p = 16, say, as there has been between p = 2 and p = 6, then the prospects of satisfactory valves for aircraft use at wavelengths down to 2 or 3 cm. are good.

3. Designs for higher power.

(a) 10 cm.valve similar to E.1189.

λ=10.66 (p = 4, d_a = 25.0, d_c = 10.0, l_a = 46, s.w. = 1.6, s.d. = 3.3, d_k = 10.0; opt.H = 1070 g., opt.E_a = 19 kV., anode dissipation about 1 kW., air cooled).

This design, of which a first sample is approaching completion, is expected to give a peak output of the order of 100 kW. Difficulties with external spark-over are quite likely to arise if this is achieved. The purpose of this design is to explore the possibilities in the direction of higher power rather than to meet any specific Service requirement. A suitable modulator has been designed.

(b) 50 cm.valve.

(See below).

The observed λ was 8.8cm.; some of this discrepancy may be accountable to slight inaccuracy in the width of the rather deep slots used; unfortunately an exact measurement of s.w. was not made during manufacture. The curve of efficiency against H showed two maxima of about 10 and 13% respectively (data for the second valve are not extensive but the two appear to agree); these occur at about 600 and 900 g. with a minimum (about 5%) near the calculated opt.H of 750g. The corresponding anode voltages were about 0.8 and 1.9 kV. An output of the order of 25W.continuous has been obtained at the higher condition but with the 200W.input required the cathode was bombarded up to far above normal temperature. The emission fell fairly rapidly during the C.W. tests but the anode current remained space-charge limited. One valve completed about 35 hours and then would not start oscillating even with over normal heating watts. The other at rather shorter life showed rapid deterioration of efficiency. On opening up both valves were found to have the central part of the nickel cathode cylinder melted and appreciably distorted. While exact figures are not available it would appear that the cathode bombardment in these valves was worse than it has been in pulse valves with the same cathode and similar mean input.

The coupling loop trial made with these valves is reported above.

Some measurements of frequency stability were made, using an H A.I. oscillator on about 50 cm. to produce an I.F. beat which was applied to a normal C.W. receiver. The method worked very well when precautions had been taken to exclude the carrier frequency from the receiver. On a rectified A.C. anode supply with a ripple of a few per cent, the frequency spread was less than 1 Mc/s (a few parts in 10^4 frequency modulation) at 1.9 kV. 70 mA input. The variation with anode voltage in the region of maximum efficiency appeared to be of the same order as that indicated by the point-by-point measurements made on E.1189 with pulsed anode voltage. Variation of frequency with anode temperature corresponded approximately to the temperature coefficient of linear expansion of copper.

The valves are now being re-made with thoriated tungsten spiral filaments (to be operated as dull emitters if the emission is stable, otherwise they can be run up to bright emitting temperature).

More complete frequency measurements will be made later.

By designing valves to work at the lower efficiency maximum observed on these samples it would appear possible to increase both anode and cathode diameter which would reduce bombardment difficulties for a given mean output.

The two C.W.valves of the "commutator" structure mentioned above are being made with oxide cathodes.

The design of indirectly heated tantalum cathodes for C.W. valves is being considered. Outgassing on the pump may present some difficulties.

6. Frequency modulation.

(a) Use of external stabilising resonators.

Preliminary experiments have shown that an appreciable reduction in frequency variation with anode voltage is possible by the use of a concentric tube resonator coupled to the tuned output circuit in the way which has been used successfully at longer wavelengths. More detailed investigation will be made later on

4. Designs for longer wavelengths.

(a) 25 cm.valves.

A first attempt to produce a valve for about 25 cm., made some time ago, was chiefly remarkable as the only case so far of gross disagreement between the calculated and the actual wavelength. The valve data were:

$p = 2$, $d_a = 13.5$, $d_c = 23.0$, $l_a = 20$, s.w. = 1.0, s.d.= 2.9, $d_k = 2.9$; calculated $\lambda = 27$ cm.; calculated operating conditions: opt.H = 1000g., opt.E_a = 7 kV. for precessional resonance oscillations, or opt.H = 735g., opt.E_a = 3.3 kV for tangential resonance oscillations.

The valve operated roughly as expected under both sets of conditions (no detailed study was made) but the wavelength was in the neighbourhood of 18.5 cm.

A radiograph revealed nothing abnormal; the valve has not yet been opened up to make sure. It is possible that the assumptions made in the wavelength calculation do not hold for large ratios of d_c/l_a. Only pressure of work on more urgent designs made us transgress the rule that in valve work experiments should never be confined to a single sample. The uncertainty as to the significance of the results which we have here is the usual penalty.

Another design, which departs less far in relative dimensions from previous valves, is now being made. ($p = 3$, $d_a = 30.0$, dc = 20.0, $l_a = 40$, s.w. = 1.5, s.d. = 5.1, $d_k = 10$; opt.H = 525g., opt.E_a = 7.6 kV.; designed $\lambda = 25.1$ cm.) The expected output is 5 - 10 kW peak.

Owing to the recent success of the oxide cathode triode E.1190 (about 20 kW peak output from a pair at 25 cm.; life data very scanty as yet but hopeful), this magnetron design is not regarded as very important from the application point of view. It is of some importance as a second string until we know more of the life and production position on the triodes. Its primary purpose is, however, as part of the experimental programme.

(b) High power design for 50 cm.

At the request of the C.V.D. Committee a design for 100 kW. peak output or more at about 50 cm.is being considered. Straight forward extension of the E.1189 design leads to clumsy structures which are also very wasteful of material unless extremely high anode voltages can be contemplated and very large powers are required.

A design is being prepared on the basis of a system of resonant copper bars each connected at one end to an enclosing copper cylinder. This looks much more reasonable but the details of the design have still to be completed. As a low field (300 g. for $p = 3$) is required in a large volume (probably d_a = 100 mm. for E_a about 22 kV) a solenoid or a pair of Helmholtz coils may be preferable to a permanent magnet.

5. C.W. Valves.

Two valves have been made, with standard oxide cathodes, for which the data are:

$p = 6$, $d_a = 10$, $d_c = 6$, $l_a = 20$, s.w. = 1.0, s.d. = 5.5, $d_k = 4.5$; opt.H = 750g., opt.E_a = 1.3 kV., $\lambda = 9.8$ cm. all calculated.

The

the C.W. valves with which precise heterodyne frequency measurement is possible.

(b) Use of internal stabilizing resonators.

Possible designs have been considered but the method has same practical drawbacks as compared with (a) and will not be pursued at present.

(c) "Squaring" of modulator wave-form.

Considerable success has been achieved in modifying the waveform of the ignition thyratron modulator in this direction. It appears, however, that with proper design of the modulator output circuit considerable squaring of the output voltage is produced by the steep rise of anode current in the operating region of the magnetron characteristic and that it is difficult to obtain much further improvement. The problem is being reconsidered from the point of view that what is required is a constant current rather than a constant voltage generator.

Tests on an actual transmitter (E.1198) and receiver have been made with both gas-filled and hard valve modulators. The results were that there was no substantial difference in frequency spread or in received signal amplitude (ground return) between the peaky and the "square" wave ignition thyratron circuits; the hard valve circuit gave an appreciable reduction in frequency spread (by a factor of rather less than 2) but the received signal was reduced rather than increased. This result is not necessarily final and the tests are continuing. The frequency spread was measured (between extinction points) by variation of the receiver local oscillator frequency. The original figure was in the neighbourhood of 40 Mc/s. Most of the radiated energy was of course contained in a considerably smaller frequency band; 1/7 of it (on a rough estimate) was contained in the 4 Mc/s pass band of the receiver I.F. amplifier.

(d) Calculation of the effect of combined amplitude and frequency modulation on a pulse signal.

A report covering this work (E.C. Cherry) will be issued shortly. In very brief summary, the result of this analysis (which is backed by some experiments at relatively low frequencies) is that for the conditions which arise in the magnetron transmitter as now used the effect of a frequency modulation of the order of several times the receiver band-width is to produce a slight increase in the peak amplitude of the received signal accompanied by some reduction of its width. A large increase in the frequency modulation would eventially so narrow the received signal as to cause loss of amplitude in the I.F. channel.

The experimental work described in (c) is now mainly directed towards getting an adequate experimental check on these predictions under working conditions. It is too early to be dogmatic but the indications are that the significance of frequency modulation in pulse transmission has been over-estimated and that the causes of discrepancies attributed to it may lie elsewhere.

.C. . . . .

M-16 CSF Experimental Magnetron

This magnetron was found in February 2024 with other experimental samples coming from the GEC Research Laboratories. Twelve anode segments are arranged to form a typical ‘squirrel-cage’ cylinder which measures about 15 mm diameter by 18 mm lenght. The segments are terminated alternatively to two lateral rings which are connected to the two top pins. The cathode is a cylinder of approximately 3 mm diameter, between the two octagonal-shaped end plates. The cathode cylinder is terminated by small ceramic spacers. The magnetron features some remarkable solutions among which the use of a large surface unipotential cathode.

The glass bulb is considerably darkened as the tube was operated for a long while at very high power. Other signs of prolonged use at the limit of power are given by the almost total lack of the getter on the inside surface of the glass bulb and by the apparent lack of oxide on the surface of the cathode cylinder.

In order to better date this sample, we must bear in mind the parallel development of the French magnetron by Henry Gutton. From the recent article ‘The cavity magnetron. not just a British invention’ (*1) we know of the meetings and exchanges of information between Megaw and Gutton, who was developing his M-16 magnetron at the CSF. In 1937 Megaw successfully tried a large surface emitter in his four-segment E880 design, a thoriated-tungsten cathode whose surface had been increased wounding the wire as a spiral (*2). He advised Gutton of the power increase made possible by this solution. Early in 1939 Gutton was obtaining about 50 W from his M-16 with spiralled wire cathode. Then he decided to try oxide-coated unipotential cathodes with impressive results. During a Megaw's visit in June 1939, Gutton showed him a sample of the M-16 generating pulses of 300 W thanks to the oxide cathode. He promised Megaw samples of the new variant. Our sources jump to May 9, 1940 when, while the Germans were occupying France, Maurice Ponte brought two samples of the M-16 promised by Gutton to Megaw almost a year earlier.

Although no code or constructors can be read on our sample, it looks very well done, with a complex and sturdy harness tightly clamped to the bottom glass column and the U-shaped ribbed terminations which held electrodes in place. The octagonal-shaped end plates and the same shape of cathode cylinder are all typical of the CSF M-16. Few doubts then that it is a CSF magnetron, a 12-segment variant of the 8-segment M-16, as it appears in the available images.

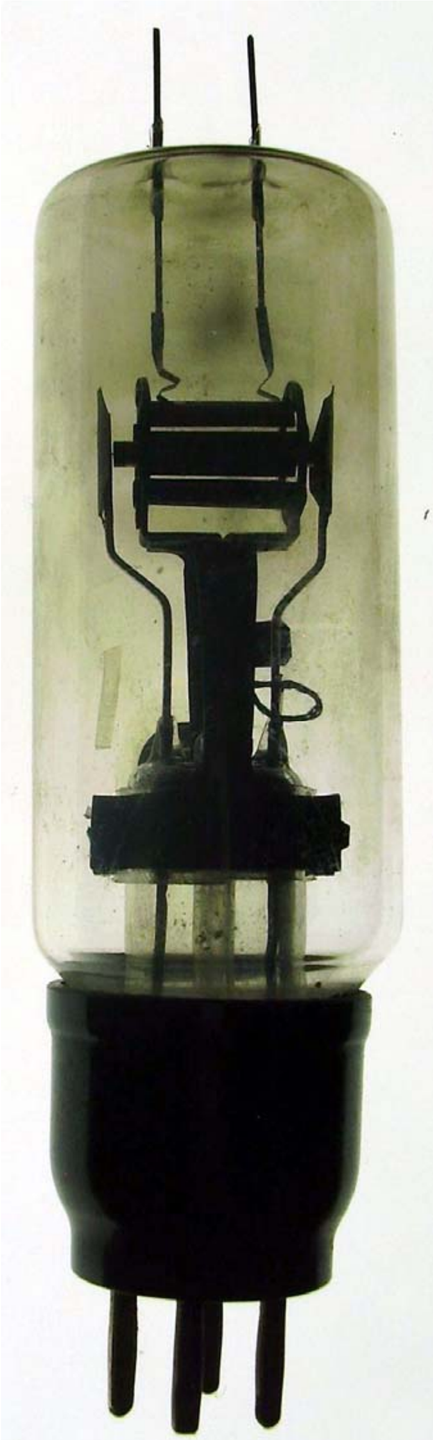
As said befor, our sample is heavily darkened, as if it was operated under extreme conditions. The fact of being together with other experimental magnetrons designed by Megaw at GEC and the evident heavy use, as if to test its limits, and even the rather crude and hasty solution of using octagonal end plates on the sides of the twelve-segment anode make us believe that this sample is one of the two designed by Gutton specifically for his friend Megaw and brought to England by Maurice Ponte in May 1940 (*1,*3). Megaw was just designing the E1189, his low-profile version of Randall and Boot's cavity magnetron, when he launched the oxide-coated unipotential cathode variant. In fact we know that the E1189 S/N 1 came out with thoriated-tungsten filamentary cathode, while the second sample, S/N 2, was fitted with oxide-coated cathode. Bench tests began for both at the end of June and the S/N 2 soon demonstrated its superior emission, with peak power reaching 10 kW. The oxide-coated cathode was just working up to expectations in the E 1190 milli-micropup triodes for the 25 cm AI under development, but no one could know whether it could work as well in a magnetron, under the effect of back bombardment. With the enormous pressure that the Air Ministry was putting on anyone capable of supplying transmitting tubes suitable for an RDF system operating at no more than 10 cm, Megaw had little or no time to waste in conducting normal tests to verify whether the new solution was efficient and reliable. He had to decide quickly wether to change a project that was still only on paper and introduce variations not yet tested. Then he had to stress the samples that Gutton had sent him well beyond their limit, to be sure that the oxide cathode could operate without damage under high-energy pulses. This could explain the visible blackening of the glass bulb and the other signs of wear on our sample.

The sample was bought on eBay UK. It is the third tube of the lot in the photo below, followed by two GEC magnetrons, prototypes of the E880/NT75 designed by the same Megaw in the 1930s.

The images below, courtesy of Yves Blanchard, represent the construction details of two eight-segment M-16s, the first with side anode connections and the second with top pins and flying wires for the heater and the cathode. The latter one was in the collection of the late Rodney Burman.

Images of our sample are given below, to quickly compare the relevant details which led us to the positive identification of the sample as a CSF M-16, although it came with other GEC experimental magnetrons. In particular we note the ribbed metal arch that supports the ends of the anodic squirrel cage, tightened with a flange to the glass column at the base. Other distinctive details are in the dimension and shape of the cathode cylinder ending in two ceramic spacers and in the octagonal shape of the side shields.



1) Y. Blanchard, G. Galati, P. Van Genderen - The Cavity Magnetron: Not just a British Invention, 2013
2) E.C.S. Megaw, High-power magnetron, a review of early experiments, 1946
3) E. C.S. Megaw, W.F. Willshaw - An aarly application of decimetre waves to communication between ships. Atti del Congresso internazionale per il cinquantenario della scoperta marconiana della radio, Roma 1947
4) E. Ciardiello - The development of E1189, the 'British cavity magnetron', 1922