The magnetron and the beginnings of the microwave age

A device of little promise, originally developed in 1916 as an alternative to grid control in vacuum tubes, became in 1940 the key to the successful development of radar by the Allied forces during the Second World War.

James E. Brittain

In the autumn of 1940, a British technical and scientific mission, headed by Sir Henry Tizard, brought to the United States a famous black tin trunk containing, among other things, an electronic device that exerted a profound influence on the outcome of the war. This device, the cavity magnetron, was developed by two British physicists, Henry A. Boot and John T. Randall, and was built at the British General Electric Laboratory at Wembley. The British at first hesitated to divulge the design of the magnetron to Americans for fear that it would fall into the hands of German intelligence, but the subsequent developments completely justified the Tizard commission's actions. The disclosure of this device led to the formation later that year of the Radiation Laboratory at Massachusetts Institute of Technology. An elite group of scientists and engineers recruited from universities and industry developed there a variety of magnetrons during the war years and incorporated them into more than 100 radar systems, giving the Allied forces a decisive technical lead. More than two billion dollars was invested in the development and production of radar systems by the United States during the war, and a momentum in microwave technology was created that persisted in the postwar period.[1]

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The cavity magnetron brought to America in the Tizard mission's "black box" had a long and complex prehistory. Albert W. Hull of General Electric Research Laboratory invented the original magnetron during a search that began in 1916 for a practical alternative to the vacuum-tube triode, which at the time was involved in patent litigation. During the early 1920s, Hull and his associates at General Electric demonstrated that the magnetron could be used at low frequencies as an amplifier or oscillator in radio systems, or as an electronic switch in power converters. The phenomenon of very-high-frequency oscillations in magnetrons was discovered independently in Europe and in Japan in the mid-1920s.

Around that time, the discovery by the Japanese electrophysicst Hidesugu Yagi and others, that relatively short waves could be used effectively for point-to-point communication, led to efforts to fabricate vacuum tubes with higher-frequency capabilities. During this research, several investigators found that the presence of ships and airplanes could be detected by reflected energy. Inherent limits of conventional vacuum tubes stimulated consideration of the magnetron as an alternative source of short waves for use in radio detection systems. The theoretical and experimental characteristics of magnetrons were investigated in at least 12 countries prior to 1939, when Boot and Randall began the work that culminated in their invention. The prewar research was carried out in a variety of institutional settings, including university, industrial and military laboratories.

The magnetron might serve as an appropriate metaphor for 20th-century science and technology as they have interacted dynamically. It is a complex device in which beams of electrons are influenced by static and orthogonal electric and magnetic fields and by traveling electromagnetic waves; it posed a challenge to the theoreticians who sought to understand its behavior and to the designers who undertook to develop magnetrons of higher frequency and power and to incorporate them in communications and radar systems. The early history of the magnetron and the related microwave revolution can provide useful insights into the relationships between science and technology in various institutional and cultural environments.

Early experiments

In 1912, Harold D. Arnold experimented with the magnetic control of mercury-vapor discharge tubes for possible use as a telephone repeater–amplifier while he was employed at Western Electric Company. He used a voice-actuated magnetic coil to modulate the arc discharge between a cathode and two anodes. The device was tried experimentally as an amplifier on the original telephone line from New York to San Francisco in 1914, but it proved less satisfactory than the improved vacuum-tube triode and was never introduced in commercial service.[2]

The inventor of the first device to be called a magnetron, Albert W. Hull,

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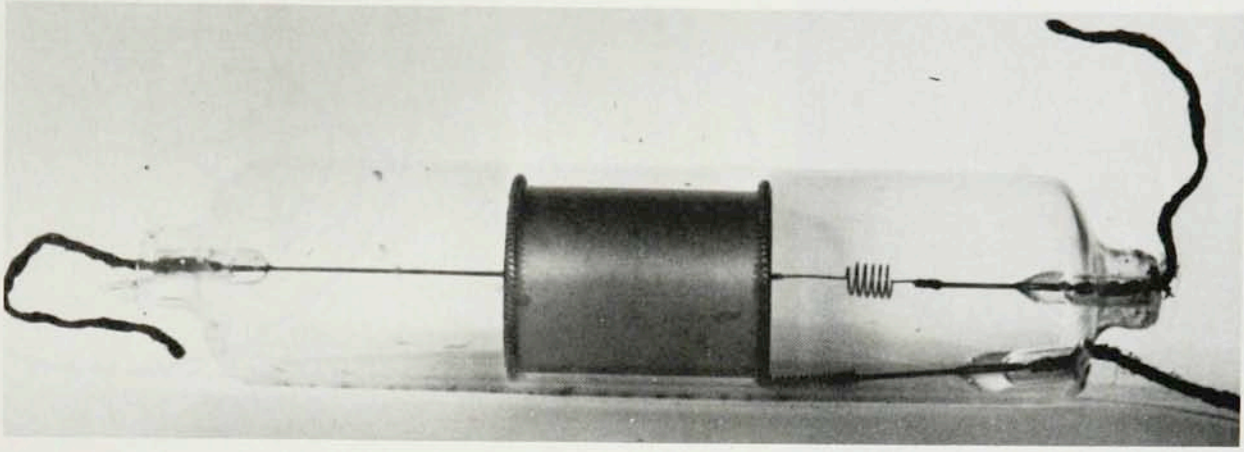

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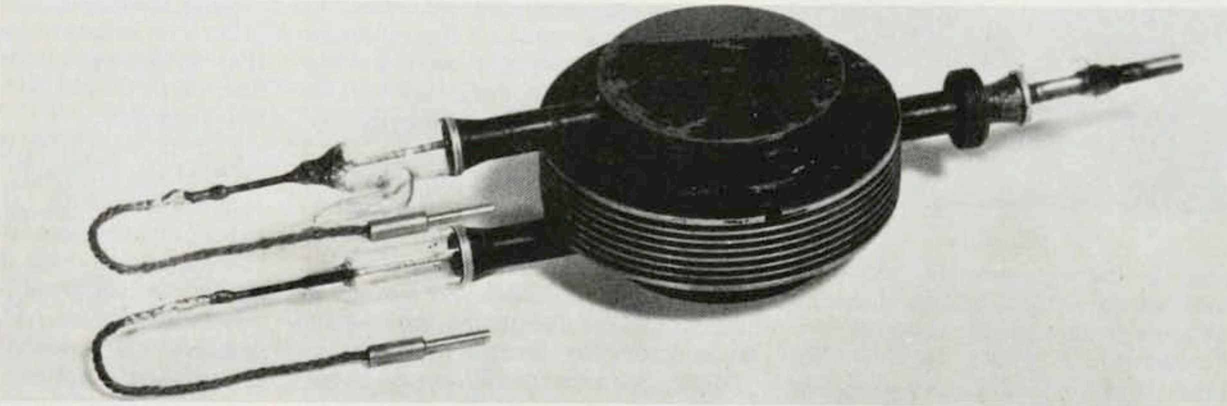

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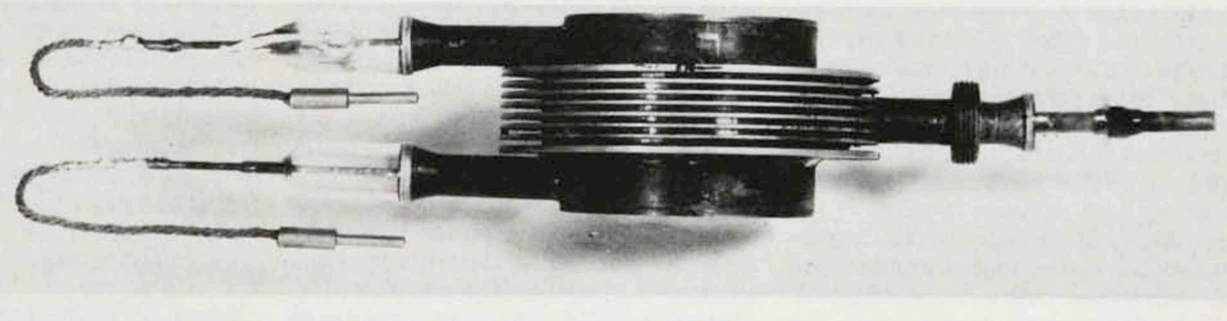

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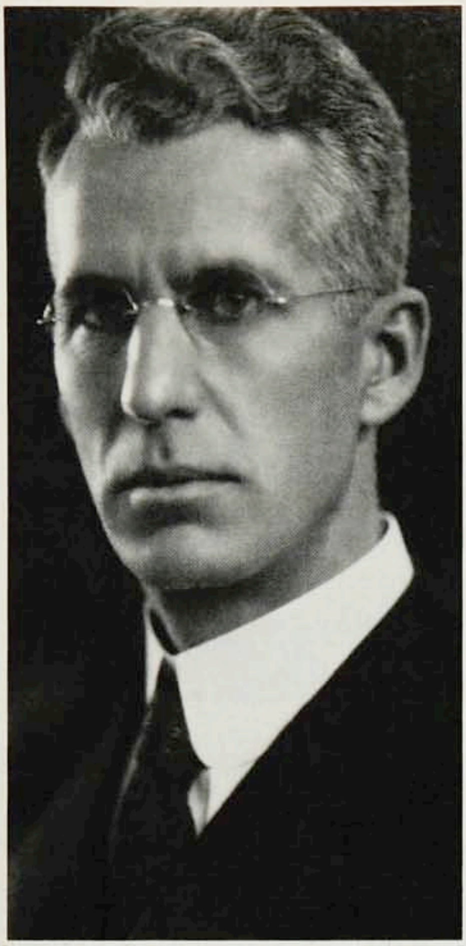
Magnetrons. a: Albert W. Hull's first magnetron. It consists of a straight wire cathode surrounded by a cylindrical anode. The British cavity magnetron **(b and c)** was brought to the US by the Tizard mission and demonstrated for the first time in the US at Bell Labs on 6 October 1940.

joined General Electric Research Laboratory in 1913. Born on a Connecticut farm, he graduated from Yale with a major in Greek and a minor in sociology. After teaching for a year at Albany Academy, he returned to Yale to do graduate work in physics. Subsequently, he taught for five years at Worcester Polytechnic Institute, until he presented a paper at a meeting of The American Physical Society that led to his employment at GE. In 1914 he invented the dynatron, a vacuum tube that exhibited a negative-resistance characteristic—the first of many electronic tubes credited to Hull. Lee de Forest coined the term "Greeko-Schenectady" for these tubes—he was critical of the proliferation at GE of tube designations, such as kenotron, pliotron and magnetron, and preferred that his own term, "audion," be used. During 1916, Hull began experiments on the magnetic control of vacuum tubes as an alternative to grid or electrostatic control. The grid control of tubes had become the subject of patent litigation between GE and American Telephone and Telegraph Company. AT&T had acquired the rights to de Forest's audion patents. Hull's investigation was initiated at the suggestion of Ernst F. W. Alexanderson, a Swedish-born electrical engineer who had joined GE in 1902 and who was directing an effort to develop a long-wave radio system based on a powerful radio alternator.[3]

In his initial experiments, Hull

GE



Albert W. Hull, who developed the first magnetron in 1916, is also known for his research with vacuum tubes and x-ray crystallography.

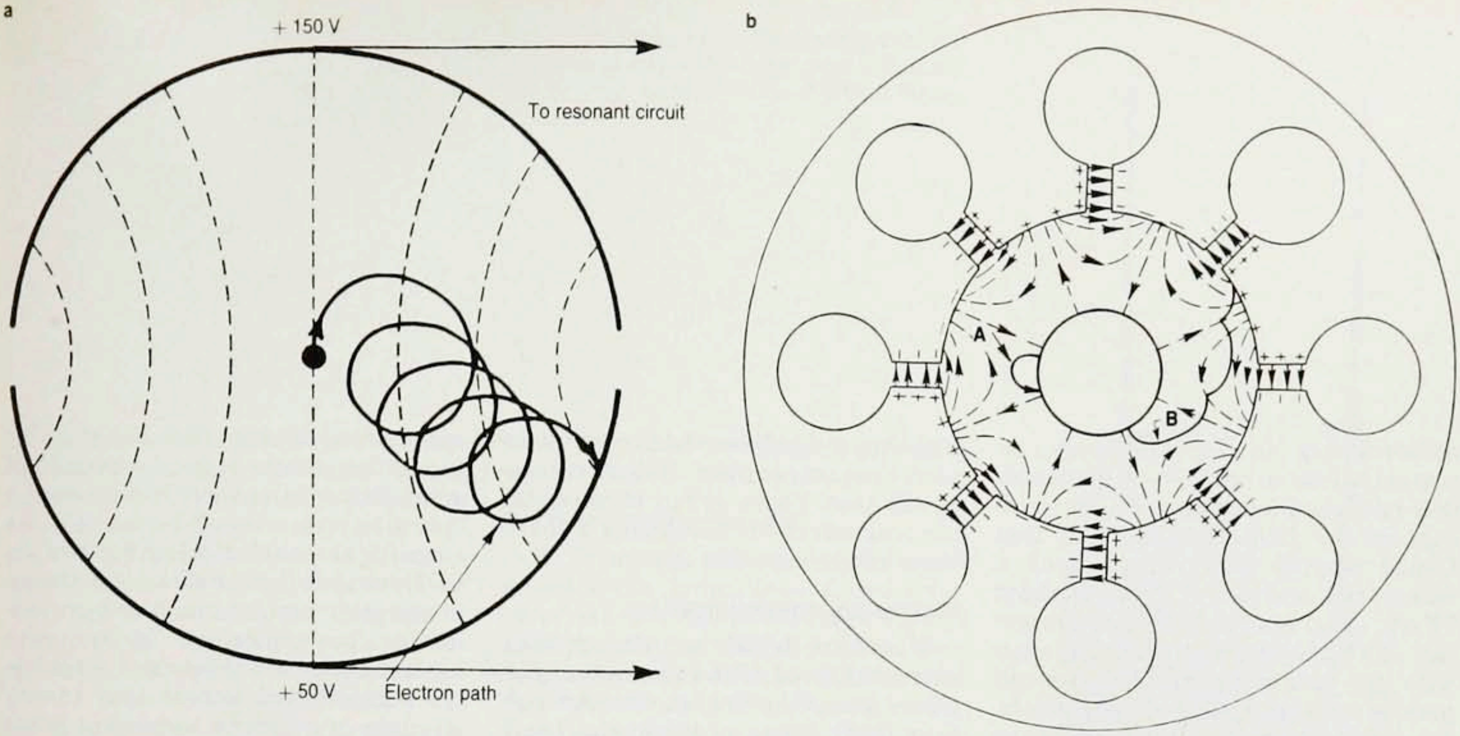
placed a target electrode where it would be barely grazed by electrons that were given a spiral motion by the influence of a magnetic field. In November 1916, he filed a patent application describing the use of a variable magnetic field in the space between the cathode and plate of a vacuum-tube diode to control the magnitude of oscillations in a resonant circuit. In a technical paper on the dynatron submitted to the Institute of Radio Engineers in 1917, he mentioned that a magnetic field oriented parallel to the axis of a vacuum tube exerted a profound effect on the tube characteristics and that voice control of the magnetic field could be used to modulate the plate current.

After the war, Hull and his GE associates resumed research on the magnetic control of tubes because of renewed concern over the vulnerability of the GE patent position on grid-controlled tubes. Terms such as "comet valve," "boomerang valve" and "ballistic electron valve" were suggested as names for the Hull tube. By early 1920, the electronics researchers at GE adopted the term "magnetron." According to Alexanderson, Laurence A. Hawkins of GERL first suggested this term.

In March 1921, Hull published a theoretical paper in *Physical Review* on the effect of an axial magnetic field on the motion of electrons between concentric cylinders. He derived equations for the critical value of the magnetic field intensity at which there is a sharp fall in the anode current for various anode and cathode arrangements.[4] Hull's paper was followed by a short contribution by the Yale physicist Leigh Page on the theory of a magnetron for the case of a variation in the electron mass at relativistic velocities. Between January 1920 and November 1921, Hull filed five patent applications on magnetically controlled tubes.

By the summer of 1921, cross-licensing agreements among the major manufacturers of radio tubes made the Hull magnetron seem less important for radio applications. Because the magnetron structure did not require a fragile grid and because it had the capability of handling high power, the GE electronics researchers continued development of the magnetron for possible use in electric power transmission. As part of that strategy, Hull presented a paper on the magnetron at a meeting of the American Institute of Electrical Engineers in May 1921. He commented that electrical engineers were used to associating electron devices with "wireless magic and microamperes read through a telescope." He continued: "... as engineers, you view them with aloofness, as interesting playthings, not engineering tools." Hull argued that such a perception was quite wrong because electron devices were not inherently small and because anode current already had reached the level of amperes and soon would reach kiloamperes. A magnetron tube with a diameter of four inches and a length of twelve inches, built at GE, had already produced several kilowatts as a power oscillator. Hull predicted that the use of magnetrons in radio would be almost insignificant in comparison to applications in power conversion, where they might replace rotary converters and enable high-voltage power transmission.[5]

During the 1920s, Hull continued to provide the scientific and engineering communities with information on the theory and the potential applications of the magnetron. He delivered a paper on the behavior of electrons in the magnetron at an APS meeting in December 1923; it described "a solid shaft of rotating electrons composed of a space lattice of equidistant electrons" for the case where the magnetic field intensity was greater than the critical value that produced cutoff of the anode current. That same year, Hull informed the members of AIEE of a new type of magnetron in which the magnetic field was produced by the filament current; the external field coil used in earlier versions was not required. This magnetron was suitable for high-power and high-voltage applications, as in the conversion of direct current to alternating current. He gave an example where such a magnetron might be used to convert 10 000 kilowatts at an efficiency of 96% and stated that this was the simplest structure and the most efficient vacuum-tube device yet investigated. In another paper published in the *Physical Review*, Hull reported using a magnetron to measure magnetic field strength. He said that his method permitted the use of a standard, portable voltmeter and gave readings as accurate as more conventional methods using galvanometers. In Hull's approach, one reads the anode voltage at the critical magnetic field and calculates the magnetic intensity from the voltage reading.



Electron paths in magnetrons. In the split-anode magnetron **(a)** the electrons emerging from the cathode follow spiraling paths toward the anodes because of the crossed magnetic and electrostatic fields. The electrons always drift towards the anode with the lowest voltage; this explains the negative-voltage characteristic of the tube. If the two anodes are connected to a resonant circuit, the electron path alternates between the two anodes with a frequency determined by the resonant circuit. In the cavity magnetron **(b)** each cavity forms a resonant circuit. During oscillation the displacement charges shown in the figure alternate at the operating frequency and the path of spiraling electrons rotates from one anode segment to the next as a traveling wave. Electrons **(A)** slowed down by the rf field return to the cathode, while electrons **(B)** accelerated by the rf field reach the anode quickly. (From *Microwave Magnetrons*, George B. Collins, ed. McGraw–Hill, New York, 1948.)

Frank R. Elder, a colleague of Hull at GERL, published a paper in the *Proceedings of the IRE* in 1925 on the magnetron as an amplifier and power oscillator in long-wave radio applications. Elder included data on eight magnetron tubes of different anode diameter and axial length. He reported that a four-stage magnetron amplifier had been tested that, under good atmospheric conditions, was capable of receiving radio signals from a low-frequency transmitter in Germany. He speculated that as much amplification could be obtained with a multistage magnetron amplifier as with the same number of grid-controlled tubes, provided careful shielding were used between stages. In a section on power oscillators, Elder described a magnetron that used a control coil weighing 125 pounds and that produced up to 15 kW at a wavelength of 15 km.[6] The GE investigators failed to detect very-high-frequency oscillations in magnetrons until after they were observed elsewhere. However, Hull commented in a paper published in *Physical Review* in 1925 that the magnetron might produce a high-frequency "Barkhausen"-type oscillation, although he had not investigated that possibility.

High-frequency oscillations

The important discovery that a magnetron in a constant magnetic field could generate very-high-frequency oscillations was reported in 1924, but did not become generally known in the United States until 1928. The Czech physicist August Zacek observed magnetron oscillations with a wavelength of 29 cm and reported the phenomenon in 1924. His paper was reprinted in a German periodical devoted to high-frequency research, *Zeitschrift für Hochfrequenztechnik*, in 1928. Also in 1924, Erich Habann of the University of Jena in Germany published a paper dealing with the negative-resistance characteristic of a magnetron that could lead to oscillation with a frequency determined by an external resonant circuit. However, according to William C. White, the papers of Zacek and Habann had not come to the attention of the electronics researchers at GERL at the time they originally were published.

Hidetsugu Yagi (1886–1976), a Japanese electrophysicist, and his student, Kinjiro Okabe, made important contributions to magnetron research and to the development of ultra-high-frequency communications, beginning in the 1920s. Yagi was born in Osaka and received an engineering degree from Tokyo University in 1909. Prior to the First World War, he studied in England under the direction of John A. Fleming, inventor of the vacuum-diode radio detector. Yagi became interested in the possibilities of high-frequency wireless communication when he spent some time in Dresden, Germany, with Heinrich Barkhausen, inventor of a high-frequency positive-grid vacuum-tube oscillator. When the war began, Yagi returned to Japan to teach at Tohoku Imperial University in Sendai, where he received a doctorate in 1919. In the early 1920s he learned of the Hull magnetron from a Japanese naval officer who had returned from a visit to the United States.

Okabe, who became the leading Japanese contributor to magnetron research, received an undergraduate degree in electrical engineering at Tohoku University in 1922 and completed a doctorate under Yagi's direction in 1928. In 1927, Okabe reported the discovery of magnetron oscillations at about 60 cm. He had experimented with a variety of electrode arrangements and found that the split-anode type produced the greatest output power. He applied for a patent in Japan in 1927 and for an American patent the following year, the latter being assigned to GE. Okabe did not learn of Zacek's independent discovery of short-wave magnetron oscillations until Zacek published his priority claim in *Zeitschrift für Hochfrequenztechnik* in 1928.

In 1928, Yagi visited the United States, where he spoke on Japanese achievements in high-frequency research before a number of audiences and published a paper in the *Proceedings of the IRE*. He disclosed that Okabe recently had produced with a magnetron oscillations down to about 12 cm. Yagi also revealed the properties of a highly directional vhf antenna with one active element and several passive reflector and director elements. He called the new antenna a "wave canal," but it became generally known as a "Yagi antenna" and still is commonly employed as an outdoor television receiving antenna. Yagi explained that the antenna was part of a "beam system" of communication under development at Yohoku University.[7] John H. Dellinger of the Radio Division of the National Bureau of Standards commented on Yagi's paper and characterized the Japanese work as "exceptionally fundamental," providing principles that would serve as a guide for further development. While in the United States, Yagi visited GERL, where the magnetron had been invented. His talk at the Laboratory was credited with stimulating the GE electronics group to develop a magnetron rated at 400 MHz, which was used for short-wave experiments at GE in the early 1930s.

In a paper published by IRE in 1929, Okabe reported that he had extended the limit of magnetron oscillations to 5.6 cm and that he speculated that the practical limit would be a few millimeters. In another paper published the following year, he made a distinction between the types of magnetron oscillations that he called "Type A" and "Type B." Okabe stated that the A type was essentially independent of an external circuit while the B type depended primarily on an external resonant circuit to determine the frequency. Another student of Yagi, Shintare Uda, participated in the short-wave research at Tohoku University. In a paper that appeared in 1930 in the *Proceedings of the IRE*, he reported that the Tohoku researchers had achieved a range of 30 km, using a beam system operated at 50 cm. Uda concluded that reliable communication over distances of more than 10 km was feasible at such short wavelengths, and that they might be especially useful for secret communication. It deserves emphasis that Yagi's group investigated the magnetron for developing a short-wave communication system.

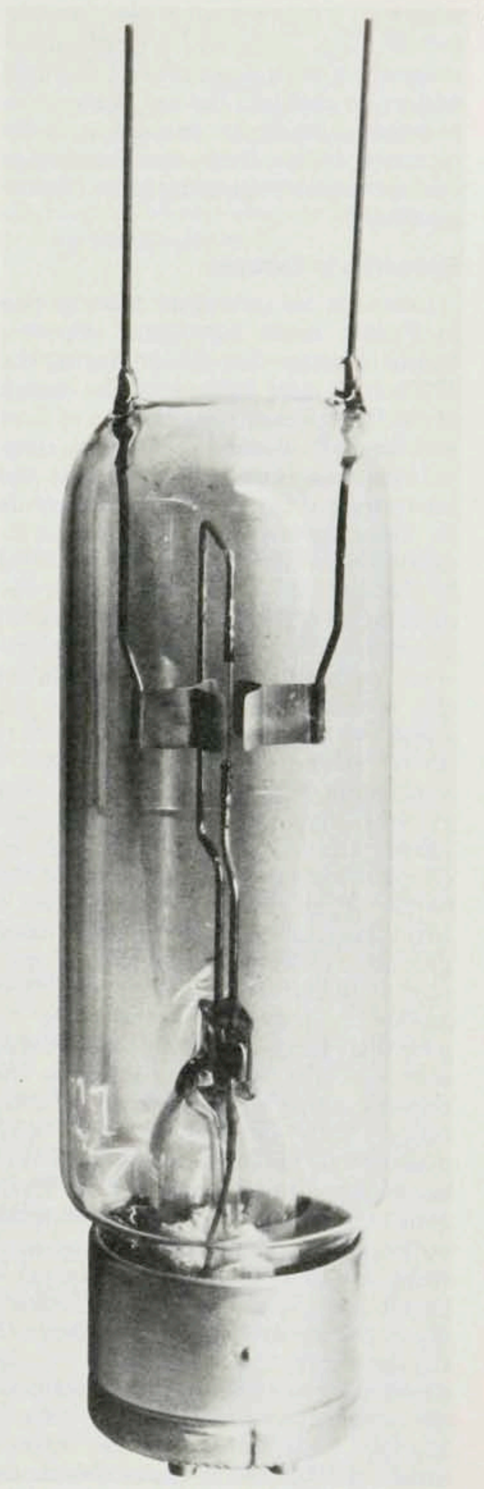
Microwave communication

A team of British and French engineers achieved two-way radio telephony across the English Channel early in 1931, using a directional beam with a wavelength of 18 cm and a transmitter power of about a half watt. The experiment attracted wide attention and helped bring the words "microray" and "microwave" into the language of radio engineering. Engineers at the Paris laboratory of the International Telephone and Telegraph Company designed the apparatus, which included parabolic reflector antennas and a transmitter that used a Barkhausen positive-grid oscillator. Soon after the demonstration on 31 March 1931, entitled "Micro-ray Radio," *Electrical Communication* carried an editorial that credited the experimental system with having opened a "veritable no man's land" that provided a frequency range broad enough for thousands of new radio channels. The editor wrote that the cross-channel experiment marked a "new epoch in the art of electrical communication" so revolutionary as to deserve a new name. The editor also noted that the apparatus was so compact that similar systems might be installed on ships or used for two-way communication with aircraft. The American periodical *Electronics* also reported the "startling announcement" of extremely short-wave telephony between Dover and Calais, and published photographs and descriptions of the apparatus. In October 1933, *Electronics* editorialized that the ultra-short wavelengths that once had been considered useless "are suddenly found to be of great importance" and "soon the scramble to stake claims in this new gold field will be on."

The perception among designers of conventional vacuum tubes, that they were approaching ultimate frequency limits caused by the electron transit time between electrodes, lead inductance and interelectrode capacitance, stimulated an increased interest in the magnetron during the 1930s. This perception seems a good example of what Edward Constant has termed[8] a "presumptive anomaly" that sets the stage for a technological revolution: As in Thomas Kuhn's well-known theory of scientific revolutions based on conflicting paradigms, a "presumptive anomaly occurs in technology not when the conventional system fails in any absolute or objective sense, but when assumptions derived from science indicate either that under some future conditions the conventional system will fail (or function badly) or that a radically different system will do a much better job."

The existence of a presumptive anomaly in the use of conventional vacuum tubes at ultra-high frequencies was reinforced by an important design priniple of proportionality, stated in a 1931 paper by Irving Langmuir of the GE Research Laboratory and Karl Compton of MIT. The principle dealt with the effect of altering the linear dimensions of a vacuum tube, and it indicated to designers how far frequency limits might be extended by simply reducing the size and spacing of electrodes.[8]

In a paper published by IRE in 1933, Browder J. Thompson and G. M. Rose of the Radio Corporation of America explained how they had applied the principle of proportionality in the design and construction of an experimental triode tube to be operated down to 30 cm. As a source for the principle, they cited the "remarkable paper" of Langmuir and Compton. The RCA researchers developed a commercial "Lilliputian triode," more commonly known as an "acorn tube," with radial leads to minimize tube capacitance and inductance. The miniature tubes were fabricated with electrode spacings of the order of 0.005 inches to minimize electron transit time. Other industrial laboratories used similar methods to develop high-frequency triodes during the 1930s. Bell Telephone Laboratories produced a tube, commonly known as a "doorknob tube" due to its physical appearance, that was capable of producing oscillations up to around 1500 MHz. General Electric developed a "lighthouse tube" for high frequencies



Split-anode magnetron built at GE. Tubes of this design have produced power outputs of 100 to 400 W at 50 cm.

by using a planar electrode structure with close spacing to minimize transit time. Despite such heroic efforts to extend the frequency range of a conventional vacuum tubes into the microwave region, the power levels achieved were quite low and the magnetron began to be viewed by some as an attractive alternative that did not suffer the same limitations. Publications on magnetrons surged[9] dramatically beginning in 1933 and remained at a high level until 1940, when the publication of papers ceased because of wartime secrecy rules.

Yagi's visit to the United States stimulated research on high-frequency magnetrons at GE and at other industrial laboratories, as well as university and military laboratories, during the 1930s. In a paper published by IRE in 1932, G. Ross Kilgore of Westinghouse Research Laboratory discussed a "magnetostatic oscillator" that he had used to produce oscillations in the range 22–50 cm. (The Westinghouse group probably avoided use of the term magnetron because it had been coined by the rival GE company.) Soon afterward, Kilgore moved to RCA, where he continued his high-frequency research and developed an ingenious experimental magnetron (a term apparently acceptable at RCA) containing argon gas that enabled him to produce visual indications and photographs of electron trajectories under various conditions. He used the device to search for a qualitative explanation of the negative-resistance characteristic of the split-anode magnetron.

Claud E. Cleeton and Neil H. Williams, physicists at the University of Michigan, did microwave spectroscopy in the early 1930s using the magnetron as a source. Initially they employed a split-anode magnetron obtained from the Westinghouse Research Laboratory. In 1933 they reported that they had fabricated a scaled-down version of the Westinghouse magnetron that produced oscillations in the 1–3 cm range. They used the device to investigate the absorption spectrum of ammonia gas. Subsequently, Cleeton and Williams conducted an experiment intended to determine the practical lower limit of wavelengths that could be generated by magnetrons. In 1936 they reported that they had obtained magnetron oscillations at 0.64 cm.

Early radar experiments

W. Delmar Hershberger and his associates at the Army Signal Corps Laboratory at Fort Monmouth, New Jersey, used magnetrons developed by Westinghouse and by RCA in experimental centimeter-wave radio detection systems (later known as radar) beginning in 1933. Hershberger had worked at the Naval Research Laboratory during 1927–31 and was familiar with a research effort on radio detection initiated by the Navy in 1930. He came to the Signal Corps Laboratory in 1931 and was assigned to develop a radio detection system for the Army in 1933. The Westinghouse Company demonstrated a microwave system using a magnetron to generate 9-cm waves at the World's Fair in Chicago in 1933. Soon afterward, the Fort Monmouth researchers acquired two of the Westinghouse magnetron transmitters. They used the Westinghouse apparatus to communicate over a distance of one mile and observed reflections from a moving truck located near the transmitter. In the summer of 1934, the group led by Hershberger conducted joint experiments with RCA engineers, using a split-anode magnetron developed at RCA that produced about 2.5 watts at 9 cm. With this apparatus they communicated successfully over a distance of 16 miles and detected reflections from a ship at a distance of a half mile. By 1936 the Signal Corps group concluded that available magnetrons would not produce sufficient power levels for practical aircraft detection systems and turned their efforts to lower frequencies (108 MHz), where vacuum tubes capable of relatively high power levels could operate.

Some relatively powerful magnetron oscillators were developed at the GE Research Laboratory by the early 1930s, but they apparently were not tested at the military laboratories. In a paper published in 1930, William O. White of GE described a water-cooled split-anode magnetron that was capable of generating 2.5 kW at 75 MHz. He discussed a second GE magnetron that produced up to 10 watts at 400 MHz. In 1936, Chester W. Rice of GE reported on experiments in which a magnetron equipped with a permanent magnet had produced a microwave beam at 4.2 cm that was used for communication at a distance of over six miles. He mentioned that he had located the transmitter and receiver in close proximity to investigate the "radio searchlight" phenomenon and had detected a moving automobile and a small airplane by means of Doppler-shifted reflections. He suggested that such a system might be used as an altimeter for aircraft or to relay television signals. Rice commented that the microwave energy was sufficient to light a carbon filament lamp and that touching the antenna wire with a finger made it feel "uncomfortably hot." He used a single-anode magnetron with a concentric filament and water cooling. His use of an alnico permanent magnet enabled a more compact design than was feasible in earlier magnetrons using large electromagnets.[10]

Research in Europe

Research in industrial laboratories in France made significant improvements in magnetron design during the 1930s that later influenced the design of the British cavity magnetron of Boot and Randall. French research on magnetrons was initiated in 1932 at the laboratory of the Compagnie Générale de Télégraphie sans Fil, using split-anode magnetrons of the type described by Okabe. M. J. H. Ponte, then the director of GTSF laboratory, reported on research with magnetrons in microwave communication in 1934 and on the operation of magnetrons in the range 7–500 cm, with power levels up to 40 W. During the summer of 1935, a magnetron designed at GTSF laboratory was installed on the oceanliner *Normandie* as part of a pulse-modulated-microwave detection system for icebergs. This system, developed by a team headed by Henri Gutton, used parabolic reflector antennas and operated at 16 cm. The French researchers made an important innovation by adopting large-diameter oxide-coated cathodes that served to increase the current rating of magnetrons substantially. They also experimented with magnetrons having anodes with 6 to 18 anode segments instead of two. Their results cast doubt on existing theories of the split-anode magnetron and later were credited with having exerted a "profound effect," on British thinking about the cavity magnetron. André G. Clavier and other members of the French engineering team that designed the apparatus used in the historic English Channel microwave experiments of 1931, also began experimenting with magnetrons in the 1930s. Clavier reported in 1939 that engineers of the International Telephone and Telegraph Laboratory in Paris had tested magnetrons down to 1.2 cm during an investigation of waveguide transmission.

Rotating-field theory

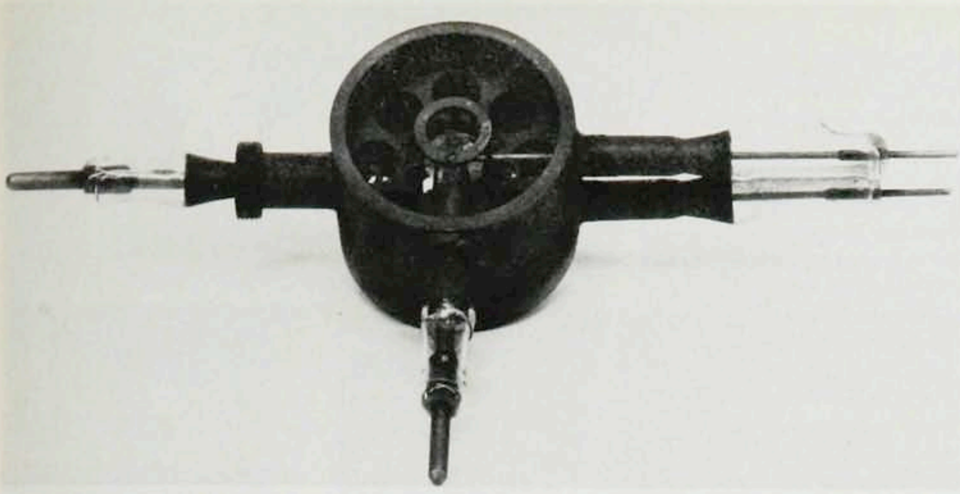
Research on multiple-segment anodes in magnetrons culminated in the development of a fruitful theoretical concept known as the rotating-field theory, which was disclosed in 1935. This theory proved a vital key in the later work by Boot and Randall on the cavity magnetron. The new theory was proposed by K. Posthumus, a researcher with Philips Company at Eindhoven in the Netherlands. In 1934, Posthumus published a brief paper in *Nature* in which he reported the discovery of a new type of oscillation in a magnetron operated with a magnetic field intensity well above the cutoff value. His analysis indicated that the frequency was doubled if four anode segments were used instead of the usual two, and he predicted that more than four would generate even higher frequencies. E. C. S. Megaw had been experimenting with multiple-segment anodes at the British General Electric Company at Wembley and wrote to *Nature* with a critique of the Posthumus interpretation. Megaw was well informed on the subject of magnetrons and magnetron theories. He had recently published a paper summarizing both magnetron theory and magnetron research since Hull's first papers. Megaw also had announced his discovery of secondary cathode emission due to electron bombardment in a split-anode magnetron, in a paper published in *Nature* in 1933. In his critique of the Posthumus paper, Megaw stated that he believed the alleged new type of oscillations actually were identical to the "dynatron type" that he had discussed in his IEE paper the previous year. He commented that he had tested a "squirrel cage" multiple-segment magnetron with negative results. Postumus responded in an item published in *Nature* that he doubted the validity of the dynatron theory as applied to the magnetron. He reported that he had produced oscillations with an eight-segment anode at a frequency four times that of a two-segment design. He also revealed that he had developed a new theory of "rotating field" oscillations in magnetrons.

Posthumus outlined his rotating-field theory in a paper published in the *Wireless Engineer* in 1935. Adapting a technique commonly used in the analysis of induction motors by electrical engineers, he had resolved the electric field due to oscillations in a magnetron into two components rotating in opposite directions. He explained that electrons in the magnetrons tended to travel tangentially in synchronism with a component of the rotary field.[11] The dispute ended later in the year with a joint contribution to *Nature* by Posthumus and Megaw. They expressed agreement that the term dynatron as applied to high-frequency magnetrons was inappropriate in view of the accurate predictions afforded by the rotating-field theory. The magnetron research at the Philips Laboratory that spawned the rotating-field theory was related to the development of a microwave communication system. In 1937 the Philips group reported that they had used a magnetron transmitter operated at a frequency of 1200 MHz to establish a radio link over a distance of 50 km.

German industrial and university laboratories also took up research on magnetrons and microwave systems during the 1930s. The Telefunken Company in Berlin experimented with a "mystery ray" aircraft detection system that was described in an article published in *Electronics* in 1935. The system employed a split-anode magnetron equipped with a permanent magnet that generated 10-cm waves. The article stated that the microwave system could locate aircraft through fog, smoke or clouds and that such detection systems were likely to revolutionize the tactics of war. Doctoral research on magnetrons was done at the University of Jena and the University of Freiburg in the 1930s, and numerous papers dealing with magnetrons appeared in German technical periodicals during the period from 1933 to 1939.

Several other university, industrial and military laboratories in Japan engaged in magnetron and microwave research that had been initiated at Tohoku University by Yagi and Okabe. Japanese researchers published at least 35 papers dealing with magnetrons during the years 1935–1940. A Japanese naval officer who had been a student of Okabe directed naval research on magnetrons conducted at the Naval Technical Research Laboratory in Tokyo and elsewhere. Magnetron research was undertaken at Osaka University, the Kawanise Machine Works in Kobe and at the Nippon Electric Company in Tokyo. The development of radar systems using the magnetron was somewhat hindered by a lack of cooperation between the Army and Navy and the absence of a centralized effort comparable to the MIT Radiation Laboratory in the United States.

By the mid-1930s, magnetron research in the Soviet Union was reported in progress at several locations. A. A. von Slutzkin of the Ukranian Physico–Technical Institute in Kharkow and several of his colleagues published papers on the effects of gas in magnetron tubes and the causes of anomalous heating of magnetron cathodes. N. F. Alekslov and D. D. Malairov of Leningrad published an important paper on their effort to obtain higher power from a magnetron in the Soviet *Journal of Technical Physics* in 1940. Their paper was later translated into English and published in the *Proceedings of the IRE* in 1944. In this paper they pointed out that the power obtained from the magnetron at ultra-high frequencies had been limited by anode heating. To overcome this difficulty, they had fabricated experimental magnetrons with cylindrical cavities drilled in a copper block, an arrangement that greatly increased heat dissipation so that one



Early copy of the British cavity magnetron. At the center is the anode block with eight resonant cavities. On the right are the leads for the current supply to the cathode. The lead for power extraction is on the left; it is connected to the coupling loop placed inside the outmost left resonant cavity. "Straps," visible in the middle of the anode structure, interconnect alternate resonators for a more stable operation.

could extract greater output power. They reported a continuous output up to 300 watts at about 10 cm and noted the possibility of using a large number of cavities. However, they did not report the use of pulse modulation, which would be needed for most radar systems, and their work apparently was not known in time to influence the work of Boot and Randall.

The cavity magnetron

Increasing British concern over the threat of German bombers provided the stimulus for the invention of a cavity magnetron suitable for use in high-power pulse-modulated radar systems. The inventors, Boot and Randall, became members of a microwave research group, headed by Mark Oliphant, formed at the University of Birmingham in 1939. Oliphant was a physicist who had come from the Cavendish Laboratory to establish a nuclear-physics research laboratory at Birmingham in 1937. Randall held a doctorate from the University of Manchester and had done research on x-ray scattering. He also had spent a year at the British General Electric Company Laboratory at Wembley, where he acquired practical experience with vacuum-tube techniques. Boot received an undergraduate degree in physics in 1938, and later a doctorate at Birmingham in 1941.

Boot and Randall investigated the multicavity magnetron in 1940, shortly after they had spent a few weeks at a radar installation. There they had learned how such systems operated and of the urgent need for a more powerful source of microwave energy. Initially they experimented with positive-grid (Barkhausen effect) tubes while other members of the Birmingham group worked on velocity-modulated tubes (klystrons). By November 1939, Boot and Randall turned their attention to magnetrons. They lacked adequate time for a comprehensive review of the already extensive literature on magnetrons, but they did study Posthumus's rotating-field theory.[12]

A key insight of Boot and Randall was to convert a two-dimensional Hertzian loop antenna into a three-dimensional cylindrical cavity resonator that served the dual function of determining the magnetron frequency and serving as the magnetron's anode. For their first experimental magnetron, they constructed a tube from a copper block, with six cavities drilled and arranged symmetrically around the cathode. They conducted a successful test of the device on 21 February 1940 and achieved a continuous power level of about 400 watts at 9.8 cm. They quickly informed Megaw at the British GE laboratory at Wembley, where the development of a microwave system for aircraft detection already was underway. By this time Megaw had learned the details of French magnetrons and of the advantage of large-diameter oxide-coated cathodes for high-power tubes. The facilities at Wembley were used to convert Boot and Randall's somewhat cumbersome experimental cavity magnetron into a more compact unit better suited for manufacture in large quantities. The Wembley engineers reduced the magnetron length so it could fit between the poles of a permanent magnet; they also used a gold-ring-seal technique developed at Wembley, which supplanted the wax seal employed by Boot and Randall, for the installation of end plates at both sides of the bored copper cylinder. A Colt revolver provided a drilling jig for the first six-cavity magnetron fabricated at the Wembley laboratory. By May 1940, a radar set using one of the new cavity magnetrons successfully detected a submarine periscope at a distance of seven miles.

The Tizard mission brought to the United States an eight-cylinder cavity magnetron that had been constructed at Wembley. It was demonstrated at Bell Telephone Laboratories on 6 October 1940 and produced 10 kilowatts peak power output at 10 cm. This was about five times the power and four times the frequency of the conventional vacuum tubes that were to have been used in the Mark I radar system under development in the US at the time. By mid-November 1940, several copies of the British cavity magnetron were made at Bell Laboratories. During the war, more than 20 types of magnetrons were developed for frequencies ranging from 1000 to 25 000 MHz (30–1.2 cm).

The device originally invented by Albert Hull as part of an effort to circumvent the de Forest triode patent had survived a period of relative neglect to become what James P. Baxter called the "most valuable cargo" ever to be imported into the US. The high-frequency mutation of Hull's magnetron spawned a large progeny and exerted a profound impact on the creation of the military–industry–university complex that continued to flourish after the war.

References

1. R. W. Clark, *Tizard*, MIT Press, Cambridge, Mass. (1965) p. 248; J. P. Baxter, *Scientists Against Time*, MIT Press, Cambridge, Mass. (1968) p. 136.
2. M. P. Fagan, ed., *A History of Engineering and Science in the Bell System: The Early Years, 1875–1925*, Bell Telephone (1975) p. 258.
3. J. E. Brittain, Adv. Electron. Electron Devices **50** (1980) p. 420.
4. A. W. Hull, Phys. Rev. **18**, 31 (1921).
5. A. W. Hull, J. Am. Inst. Elect. Eng. **40**, 715 (1921).
6. F. R. Elder, Proc. Inst. Radio Eng. **13**, 159 (1925).
7. H. Yagi, Proc. Inst. Radio Eng. **16**, 715 (1928).
8. C. G. Suits, H. E. Way, eds. *The Collected Works of Irving Langmuir* Vol. 4, Pergamon, New York (1960–62) p. 388.
9. See the magnetron bibliography in A. F. Harvey, *High Frequency Thermionic Tubes*, John Wiley, New York (1943).
10. C. W. Rice, Gen. Electr. Rev. **39**, 363 (1936).
11. K. Posthumus, Wireless Eng. and Exp. Wireless **12**, 126 (1935).
12. H. A. H. Boot, J. T. Randall, IEEE Trans. on Electron Devices **23**, 724 (1976). □