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Review article: Microwave tube development in Germany from 1920-1945

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Review article

Microwave tube development in Germany from 1920–1945†

H. DÖRING‡

The state of electron tube development in Germany at the beginning of the period is briefly reviewed. At higher frequencies the conventional grid-controlled triodes fail to work owing to lead and electron transit-time effects. It is shown how these effects can be reduced or made useful for the mechanism of the tubes. Compact triodes in metal–ceramic technology were developed for CW and pulse operation in the dm and cm bands. They have been combined with coaxial resonators. Finite transit-time was first utilized in 1920 in retarding field tubes. Beginning in 1924, zero and multisplit magnetrons with transmission line resonators were developed as oscillators. They were used in search receivers. Multicavity magnetrons were introduced in 1944. Although amplifier klystrons began to be developed in 1939, these were not used in wartime. However, a special klystron, the tunable Heil oscillator tube, came into practical use; a reflex klystron copied from captured equipment was modified and also used.

1. Introduction

It is necessary to start the review by describing the early stages of electron tube development in Germany in order to show why the traditional grid controlled tube, as used in radio receivers, failed to work at sufficiently high frequencies. As a tube design engineer of long standing, the author is very familiar with most of the problems and solutions encountered at the time.

The development and production of high vacuum electron tubes started in Germany at Telefunken, well before the beginning of World War I, the company having been created in 1903 by the joint efforts of AEG and Siemens. Later in 1911 the so-called 'von Lieben Konsortium' was founded by AEG, Siemens, Telefunken and Felten & Guilleaume specifically to evaluate the von Lieben patents. Robert von Lieben in 1906 was granted a patent for an inertia-less relay using a gas filled amplifier tube. Such a deflection controlled tube was in fact a combination of Wehnelt's oscilloscope tube (1905) and Perrin's cold cathode tube with a screened anode (1895). (I am grateful for this information to Kaye Weedon.) Von Lieben, together with his co-workers Reiss and Strauss, modified the tube in 1910 by inserting a control grid between the cathode and the anode. In 1907 a similar device was proposed in the U.S.A. by Lee de Forest: he called it the 'Audion' and described it as an 'improved detector and amplifier'. Both devices were unstable owing to the presence of ionized gas and they only worked at low anode voltages. Nevertheless, Telefunken were able to demonstrate 'von Lieben amplifiers', developed by AEG, at a congress on wireless telegraphy held in

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Disturbing effects	Remedies: Straight reduction	Remedies: Deliberate use of the effect
Lead effects	1. Low capacity design: short, thick pins as leads, several pins in parallel (reduction of inductance and resistance)	2. Thin sheet leads (cylindrical or plane) forming part of coaxial or cavity resonators
Transit time effects	3. Reduction of the (transit time/ period of oscillation) ratio in grid controlled tubes: close electrode spacings, high operation voltages	4. Planned interaction between electron beams and localized or travelling electric fields

Table 1. Lead and transit time effects.

London in 1912 (Rukop 1928). Also in September 1914 a telephone repeater using a von Lieben tube secured good reception over a distance of 1200 km on the line connecting the German Imperial HQ and East Prussia.

An important step in the development of electron tubes was the realization that they require a good vacuum for successful operation. At the beginning of 1914 the patents granted to Langmuir in the U.S.A. became known in Germany. They greatly contributed to the realization that the epoch of gas-filled triodes, as originally developed by Lee de Forest and Robert von Lieben, was over. As an immediate result, both Telefunken and Siemens left the von Lieben Konsortium. Siemens then developed, in collaboration with Pirani and later Schottky, their first high vacuum electron tubes, the work being carried out in an electric lamp factory. In May 1914 Telefunken decided to establish a separate centre for tube development and manufacture under the guidance of the physicist Rukop (Rukop *et al.* 1935). Here they first used rotating mercury pumps, soon replaced by the more efficient molecular pumps, all made by W. Gaede. At the beginning of World War I, the first two-stage amplifier using high vacuum triodes was successfully demonstrated on 1 August 1914; by the middle of the war transmitters and receivers equipped with vacuum tubes became generally available. When in 1923 the first public broadcast transmitter was built in Berlin, other companies also entered the field of electron tube manufacture.

In due course, as the frequency range expanded towards higher frequencies, difficulties began to be experienced with conventional receiving tubes: as is well known, at sufficiently high frequencies conventional tubes begin to attenuate the input signal, the tube transconductance becoming complex and its magnitude decreasing with increasing frequency. This rapidly leads to a severe drop in overall amplification. Also, an upper frequency limit is experienced when the tubes are used as oscillators. The two different origins of the above difficulties are shown in Table 1.

The first disturbing effect is caused by the presence of leads connecting the electrodes and the socket pins, including the interelectrode capacitance in what follows these will be called 'lead effects'. Secondly, at sufficiently high frequencies the usual mechanism of operation of the tube is disturbed by the fact that it takes a non-zero time for the electrons to traverse the interelectrode space. When the transit time is no longer negligible compared to the period of oscillation of the signal being amplified, 'transit-time effects' arise; both lead and transit-time effects cause the appearance of a resistive component in the input admittance of the tube which increases as the square of the signal frequency. These effects can be either obviated by a suitable design of the tube (1 and 3 in Table 1), the limiting frequency being thus shifted towards higher values, or they can be made use of (2 and 4 in Fig. 1) by the development of the so-called 'transit time' tubes, where they become an integral part of the mechanism of operation. For example in the case of conventional tubes lead effects can be reduced by mounting the electrodes directly on short, thick tungsten or molybdenum pins penetrating a flat, glass base, rather than on a pressed glass structure resembling that used in ordinary electric bulbs, a technique which was common till 1935. The new method of mounting the electrodes also eliminated the need for a separate tube socket and in addition made it possible to connect the leads directly to an outside parallel plate or coaxial transmission line or, even use them as an integral part of a resonator.

In conventional tubes transit-time effects can be reduced by diminishing interelectrode spacing, in particular that between the grid and the cathode, and by operating at higher anode voltages. However, production and operational requirements impose a practical upper limit for triodes at a few centimetres wavelength. Yet, abandoning the grid-control mechanism altogether, one can use the transit-time effect to develop a whole range of entirely new devices such as retarding-field tubes, klystrons, magnetrons and travelling wave tubes.

2. Grid-controlled tubes (triodes)

It has been shown in the introduction that in triodes it is possible to reduce the problem caused by both lead and transit-time effects. Quite early, lead effects were reduced by keeping grid and anode connections short and taking them through the glass envelope at different points, thus reducing the associated capacitance in low power transmitting tubes (Kühle 1932). Feedback oscillators using conventional triodes but without sockets, together with three-terminal circuits consisting of a tapped wire loop for inductance and inter-electrode separation for capacitance, made it possible to generate much higher frequencies. They were primarily developed at universities, for example by A. Esau at the Technisch-Physikalisches Institute of Jena University, and were used for the investigation of wave propagation and the properties of materials at very high frequencies.

In the U.S.A., White (1916) developed a triode oscillator by using a shorted parallel-wire transmission line as the resonator. He managed to obtain 10 W output power at 6 m wavelength. To the best of my knowledge this was the earliest example of a transmission line used as a resonator in an electron tube oscillator. In 1921 E. Holborn, working at the Telegraphische Reichsanstalt in Berlin, reported the successful operation of a push-pull oscillator using two Siemens RS 5 triodes. As shown in Fig. 1, instead of lumped components two short-circuited $\lambda/4$ transmission lines were used—they were respectively connected between the grids and the anodes of the two tubes (Holborn 1921).

The damaging effect of the electron transit-time was reduced by decreasing the separation of the electrodes, in particular the cathode–grid spacing, but not without adversely affecting the available output power. In the mid-thirties, most

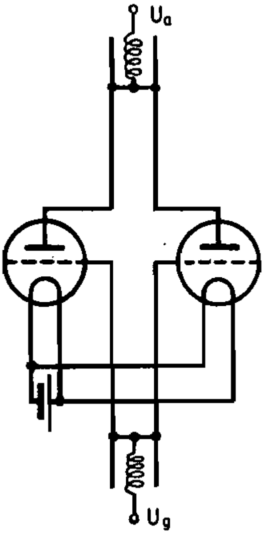

Figure 1. Push–pull circuit using resonant transmission lines (Holborn 1921).

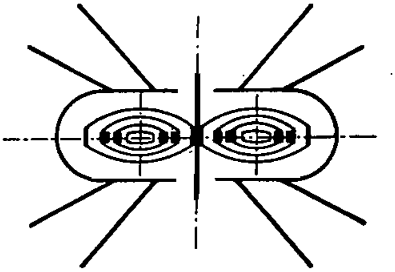

Figure 2. Electrode arrangement of the twin-pentode RS381 (Telefunken) (Hülster 1940).

tube manufacturers abandoned the idea of a base in the form of a long glass stem with electrode leads running through it, the technique initially borrowed from the production of the incandescent lamp (Kleen 1940). Telefunken, for example, initiated the development of robust tubes, the so-called 'Stahlröhren', using steel rather than glass envelopes and an electrode system placed close to a metal base plate pierced by short, carefully insulated leads. Similarly, C. Lorenz AG developed saucer-shaped (Napfform) pressed glass bases for small receiving tubes (Behne and Herriger 1955); such tubes could be used with or without a special socket. Without a socket they were frequently used in battery operated transmitters and receivers; for example a small RD 12 Ta triode could provide 0·8 W output power at 30 cm. Double diodes, based on a similar manufacturing technique, for rectification and mixing at 10 cm also became available. At the same time variants of American acorn-tubes were also fabricated in Germany. Further examples of small, space-charge-density controlled microwave triodes developed just before and during World War II (Wehrmachtströhren) (Müller 1962) will not be discussed here since their development did not involve any new ideas and they were often designed solely to satisfy the competing requirements of the three branches of the armed forces.

For higher powers pressed, hard-glass plane bases were used, thick tungsten leads giving rise to relatively low high-frequency losses; such bases could be directly inserted into tube sockets (see also 1 in Table 1). A good example of such modern design techniques can be found in RS381, a double-pentode operating in the 1 m range and shown in some detail in Fig. 2 (see also Hülster 1940). Here the two suppressor grids are attached directly to a metal sheet separating the two sections of the tube and the screen grids are connected together by thin metal ribbons, their wires shadowing those of the corresponding control grids. The cathodes, which are approximately oval in shape, are coated on their broad sides only, so that each cathode generates in effect two independent electron beams; lastly the anodes are respectively connected to two separate pins placed on top of the tube envelope. The tube was designed to operate at wavelengths as low as $\lambda = 80\,\mathrm{cm}$; when used in a type-B amplifier it could deliver 35 W at $\lambda = 1\,\mathrm{m}$ and 120 W at wavelengths exceeding 10 m. Concurrently a push–pull high-frequency triode called LS600, was being developed; when used as an oscillator it could generate 160 kW pulses at $\lambda = 55\,\mathrm{cm}$, the frequency of oscillations being adjustable within $\pm 10\%$ using an externally coupled resonant transmission line, part of the circuit being inside the glass envelope of the tube (Rukop *et al.* 1935).

Once the manufacture of plane, pressed-glass bases had been mastered, the production of tubes incorporating more complicated lead arrangements became possible. RD12Tf shown in Fig. 3 is a good example of such a tube. It is a triode developed during World War II in the Transmitting Tubes Laboratory of C. Lorenz AG under the direction of F. Herriger. The actual layout of the leads is shown in Fig. 4(*a*). The planar glass base has room for thirteen connections: two for the cathode, two for the heater, three for the grid and two sets of three, one set for each side of the anode. In thise case it is therefore possible to use a three-element parallel-plate transmission line as an external resonator by connecting it between the grid and the two sides of the anode (Behne and Herriger 1955). These tubes were capable of delivering 50 kW pulses at wavelength of 53 cm and they were manufactured in fairly large quantities. The design, especially that of the cathode, was based on new ideas concerning the permissible cathode current density for pulse operation. In the construction of the tube, aluminium-plated iron sheets were used for the anodes. The aluminium coating, which is initially quite bright in appearance, changes its colour to dark grey at the high temperatures prevailing during evacuation and baking; this greatly improves the thermal radiation properties of the anodes so that under the same loading they reach a much lower temperature.

The most important triode development in Germany, resulting from military requirements, was due to the introduction of plane or cylindrical metal sheets in place of high-frequency leads, protruding through the base; at the same time cylindrical electrodes were replaced by plane electrodes. This change amounted to the combination of 2 and 3 in Table 1, the unavoidable electrode leads thus directly becoming part of an external resonator circuit. In spite of extremely small electrode spacing, especially between the cathode and the grid (required for high-frequency operation), it proved possible to achieve large-scale production; this was helped by the use of plane, or only slightly curved electrodes. In order to manufacture such disc-seal tubes (Scheibenröhren) successfully, it was first necessary to develop suitable metal–glass seals. After an initial investigation of copper–glass and fernico–glass seals, it proved best for reasons of mechanical stability and temperature control to use metal–ceramic seals. Employing this newly developed technology, Telefunken manufactured a large variety of robust and very compact

Figure 3. Pulse-triode RD12 Tf (C. Lorenz AG) (Behne and Herriger 1955).

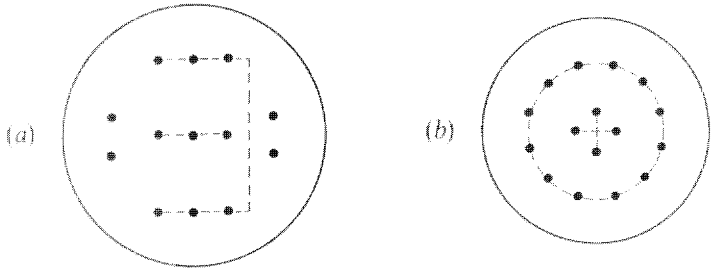

Figure 4. Pressed glass plane bases suitable for connection with resonant transmission lines (*a*) for RD12 Tf, (*b*) for RD12 La.

triodes for the lower decimetre range of waves (Steimel 1942). Here metal cylinders, acting as 'leads', form an integral part of two coaxial line resonators forming input and output circuits, the tubes being mostly used as grounded grid amplifiers. A cross-section of a disc-seal tube is shown in Fig. 5, where the cathode and the grid are slightly curved in order to avoid undue distortion caused by heating, an external radiator being attached to the threaded part of the anode protruding through the seal. The tube can be operated as an amplifier or an oscillator, in the latter case coupling being achieved by inserting suitable pins in the circular-ring part of the grid connection. As an example, the triode LD9 was able to generate 20 W CW at a wavelength as short as 8 cm and the LD13 could

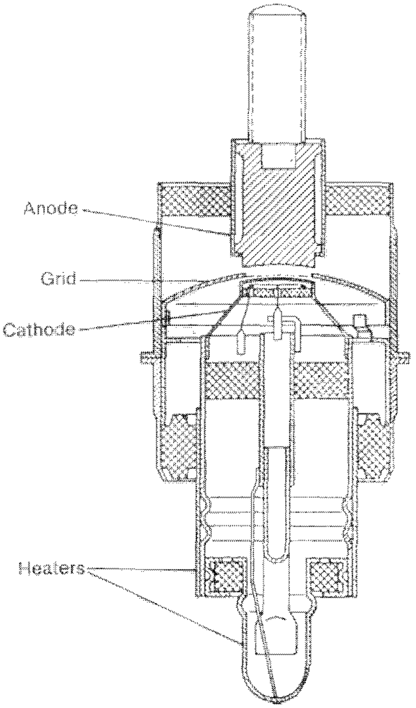

Figure 5. Longitudinal section of the metal–ceramic triode LD12 (without the cooling jacket).

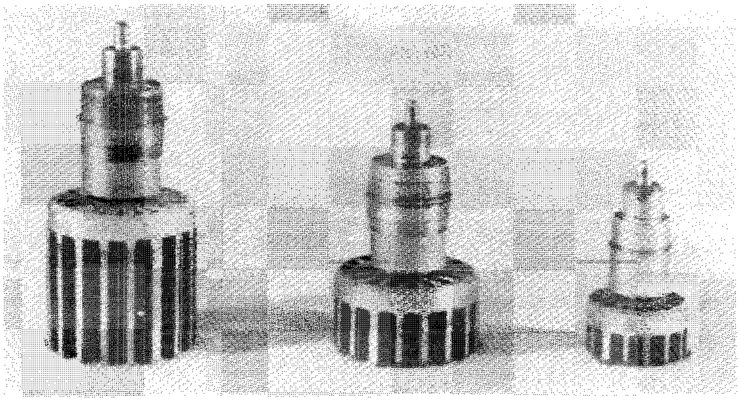

Figure 6. Metal–ceramic triodes LS500, LD7, LD11 (Telefunken) (Rukop *et al.* 1935).

generate 120 kW pulses at 25 cm (Müller 1962). Three different metal–ceramic triodes are shown in Fig. 6.

One can easily say with hindsight that the very success of the metal–ceramic triodes, used in the decimetre-range during World War II in Germany, substantially delayed research and development on transit-time devices, in particular klystrons. Some people claimed that triodes, when properly designed, could fulfil all requirements. Such views were encouraged by an apparent failure to realize the clear military advantages of centimetre waves. A radical change of view among the

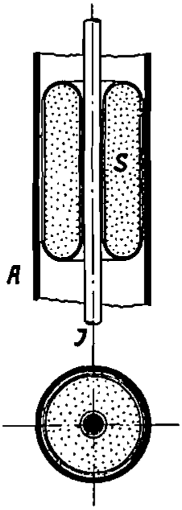

Figure 7. TR-tube (without electrodes) as mounted in a coaxial-line (Nullode) (Rukop 1948).

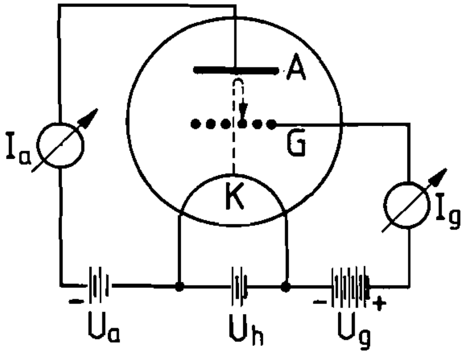

Figure 8. Retarding-field tube and its circuit (Barkhausen and Kurz 1920).

military occurred when in February 1943 a British bomber was shot down near Rotterdam and it was found that its radar set contained a high power magnetron and a reflex klystron, both operating at a wavelength of approximately 9 cm!

At this point one should also mention a type of tube designed for blocking propagation along a coaxial line, rather than for the generation or amplification of decimetre waves; such tubes were called 'Nulloden', the name being derived from the German word 'null' or 'zero' ('TR-cells' in English). These tubes have no metal electrodes and are simply filled with water vapour and traces of radioactive elements. They have the shape of an elongated torus or doughnut and are inserted directly into the space between the inner and outer conductor of a coaxial line, as shown in Fig. 7. Their task is to protect sensitive parts of the radar equipment, when both the transmitter and the receiver are connected to the same antenna; by firing under the influence of pulses generated by the transmitter they would eliminate the voltage spike which would otherwise appear at the input to the receiver. Such Nulloden tubes, for example LG71 and LG73, were developed at Telefunken by Joh. Müller; some of them (LG75) were provided with an outer metal coating. The design shown in Fig. 7 was adequate for operation at 30 cm and above; for shorter wavelengths it proved necessary to use copper–glass seals, the tube being inserted directly into a resonator cavity (Müller 1962, Rukop 1948).

3. Transit-time tubes

3.1. *Retarding-field tubes*

The retarding-field tube can be regarded as the first transit-time tube. It was invented in Germany by H. Barkhausen in 1920. Already during World War I Barkhausen was asked to write a military manual on the operation and applications of electron tubes. The manual was later enlarged to become a textbook on electron tubes, its first edition appearing in 1923. During some measurements on a triode with a positive grid and a negative anode (Fig. 8) Barkhausen and H. Kurz noticed irregularly fluctuating anode currents (Barkhausen and Kurz 1920); Barkhausen interpreted them as self-excited oscillations generated by the tube. Later they were known as 'electron dance oscillations' on account of the oscillatory motion of the electrons around the wires of the grid. Owing to the existence of a retarding field between the grid and the anode the name 'retarding-field tube' was generally adopted. It is interesting to note that the three effects characteristic of transit-time devices are already present in the retarding-field tube: they are velocity modulation, bunching (i.e. conversion of velocity into density modulation) and power transfer from the beam to the circuit. This was the first tube in which the unavoidable transit time effect was put to good use. In 1920 the shortest wavelength which could be reached using commercially available triodes was 43 cm. Owing to their simple design, such triode oscillators became very popular, especially among University Institutes. They were mostly used as high frequency local oscillators and sources of oscillations for various measuring instruments. In order to achieve higher frequencies and higher output powers early variants of the original Barkhausen tube, which had no separate resonant circuit, were investigated. In what follows some typical examples of such developments will be discussed.

K. Kohl mounted an inductive wire loop inside the envelope of the tube and, using the capacity between the helical grid and the cylindrical anode, generated oscillations at 30 cm wavelength (Kohl 1930). In his doctoral dissertation submitted to Jena University, A. Scheibe investigated a tube whose grid and anode were joined to two parallel wires piercing the glass envelope of the tube, so that an external resonant circuit in the form of a shorted transmission line could be used (Scheibe 1924). Using this particular arrangement, oscillations in the range of 24–300 cm were generated in 1924.

A similar principle was employed in Jena by Pfetscher and Müller (1934). They investigated devices with resonant transmission lines (parallel wire or coaxial) placed inside the glass envelope. The RF electrodes, the grid and the anode, were mounted either at the open end of a shorted $\lambda/4$ transmission line, or in the middle of a $\lambda/2$ line shorted at both ends, or even at the ends of a $\lambda/2$ long line. These were fairly obvious developments and have also been used with other tubes. In addition, K. Kohl managed to generate the so-called 'helix oscillations' by connecting both ends of the grid helix with a piece of wire (Kohl 1930); by reducing the dimensions of the electrodes and converting the grid helix into a

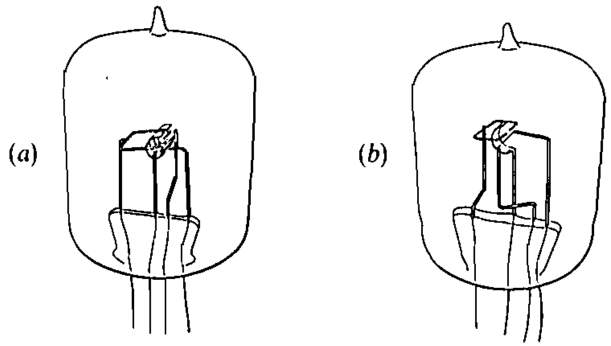

Figure 9. Retarding-field tubes designed to operate at the following wavelengths: (*a*) $\lambda = 10\,\text{cm}$, (*b*) $\lambda = 7\,\text{cm}$ (Kohl 1930).

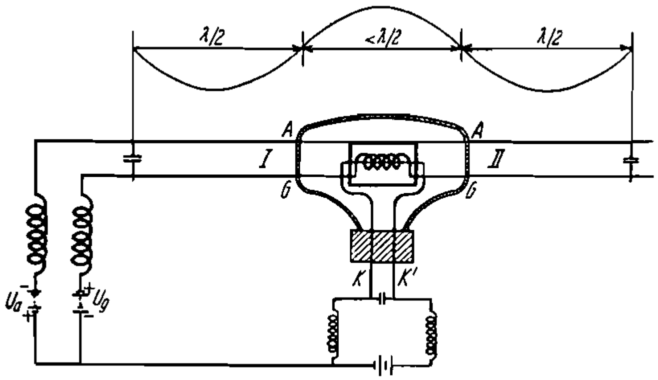

Figure 10. Retarding-field tube RS296 and its circuit.

single loop, he was able to bring down the wavelength of oscillations to 4·7 cm, with a corresponding output power of the order of a few milliwatts. Figure 9 shows similar devices respectively operating at 10 and 7 cm. Kohl also reported the existence of a device operating at 24 cm, using a water-cooled grid and consuming 200 W of power.

As the result of a proposal by Hollmann (1932), two tubes, RS295 and RS296, were developed at Telefunken by Kühle (1932). They were characterized by the fact that the electrodes were mounted in a T-shaped glass envelope, as shown in Fig. 10; a pair of leads, one for the grid and one for the anode, were brought out on either side, a tunable transmission line being connected to each pair of leads. At the base of the tube, only two leads for the directly heated cathode were now necessary. In order to reduce dielectric losses in the glass envelope of the tube, the RF leads were so dimensioned that voltage nodes were made to occur where the leads pierced the envelope. Furthermore, the grid, which was bombarded by the electrons (an effect which limits the achievable RF output power) was carefully designed to dissipate the maximum amount of heat. Figure 11 shows RS296 which was used by F. Herriger to achieve a power output of 5 W at 50 cm (Herriger 1934). In a further development along somewhat similar lines in 1936, H. Dällenbach and his co-workers built for Pintsch AG a tube comprising cylindrical electrodes forming part of a coaxial line resonator which was shorted at both ends

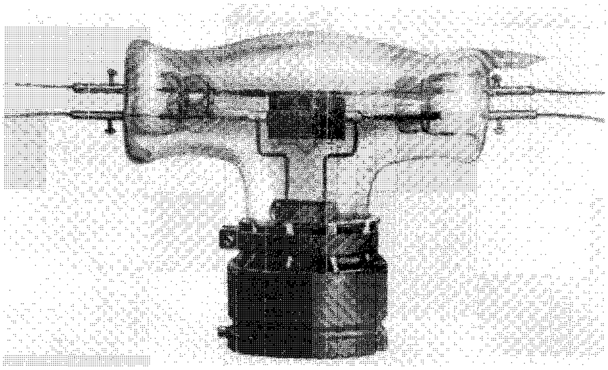

Figure 11. Retarding-field tube RS296 (Telefunken) (Kühle 1932).

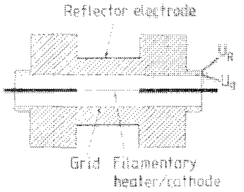

Figure 12. Schematic design of the 'resotank' tube (Pintsch) (Allerding *et al.* 1938). (The electromagnetic field extends over the shaded portion of the tube.)

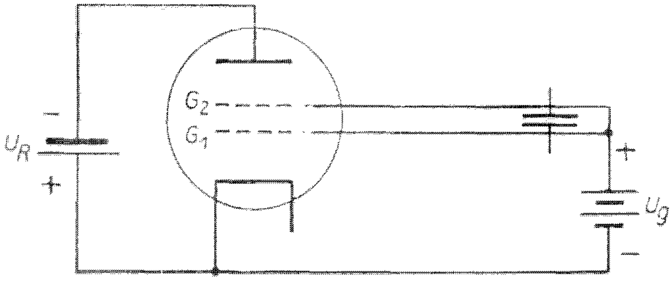

Figure 13. Double-grid retarding-field tube using a resonant transmission line, proposed by Hollmann (1929) (DRP 1929).

(Allerding *et al.* 1938). A schematic design of this so-called 'Resotank' is shown in Fig. 12. The middle part of the inner conductor acts as a grid, a filamentary cathode being mounted along the axis, the outer conductor acting as a reflector over its central section, where its radius is substantially reduced. These tubes were capable of generating almost 1 W of output power at 14 cm, but they were tunable only over a very narrow bandwidth. One should add here that F. W. Gundlach and W. Kleinsteuber made valuable contributions to the theory of the operation of retarding-field tubes; in particular they managed to obtain good agreement between theory and experiment in the case of the 'Resotank' tubes (Gundlach and Kleinsteuber 1941). Although the two retarding-field tubes described above reached a degree of manufacturing maturity, to the best of my knowledge they have never been used in miliary equipment, in contrast to magnetrons and klystrons.

The principle of operation of a reflex klystron was anticipated by H. E. Hollmann as early as 1929 who patented a 'double-grid retarding-field tube' (DRP

1929). A drawing copied from the patent specification (Fig. 13) shows a parallel-wire transmission-line resonator connected between two positively biased grids. In a later patent specification (DRP 1935) the transmission line resonator is replaced by a coaxial line or a cavity resonator. However in 1929 it did not prove possible to achieve oscillations using such a double-grid tube, probably due to field leakage and excessive losses in the transmission line resonators (Hollmann 1957).

3.2. *Magnetrons*

Research on magnetrons started in Germany when E. Habann published his doctoral thesis in 1924 (Habann 1924). The paper described theoretical and experimental investigations of a cylindrical vacuum device comprising a filamentary cathode surrounded by plane parallel or semi-cylindrical electrodes, all immersed in a constant magnetic field parallel to the common axis of symmetry. Habann correctly predicted the conditions required for the appearance of a negative resistance which would overcome the usual damping caused by the resonant circuit losses. In contrast to the Hull device (Hull 1921) Habann used a magnetic field which was constant in time. Using his split-anode magnetron Habann was able to generate oscillations in the 100 MHz range (Runge 1934).

The Telefunken company purchased Habann's patents and in 1934 started its own magnetron development programme, having first investigated two British split-anode magnetrons developed by F. C. S. Megaw and capable of generating 5 W at 50 cm. Under the direction of W. T. Runge, new two-vane and four-vane split-anode magnetrons were soon successfully developed (Runge 1934). Meanwhile, various mechanism for the excitation of oscillations in a magnetron became known. F. Herriger and F. Hülster studied such problems and soon were able to identify various modes, including the travelling-wave mode, which is the only mode of interest in present day magnetrons (Herriger and Hülster 1936).

Besides industrial research and development laboratories (Telefunken, Blaupunkt, Sanitas, Gema), many university and government research institutes became engaged in this field of research. In the Physikalisch-Technisches Institute of the University of Jena a group under A. Esau was successful in generating oscillations at very high frequencies and of relatively high power, mostly for electromagnetic wave propagation experiments and for investigations of the high frequency properties of materials. Esau and Ahrens (1937) reported the development of a magnetron with an internal transmission line resonator and operating at 4·8 and 2·8 cm. H. Richter (1938) using a slightly different arrangement achieved oscillations at wavelengths as low as 0·49 cm. O. Pfetscher and Puhlmann (1936) developed watercooled tubes, which were initially continuously evacuated. Two such devices, where the resonant lines are used for cooling the anodes, are shown in Fig. 14. Tube (*a*) was directly cooled and operated over the range 98–400 cm; typically at 100 cm it would deliver 850 W output with an overall efficiency of 55%. Using indirect cooling, tube (*b*) would deliver 800 W at 19 cm. Ahrens (1937) designed magnetrons with water cooled resonant lines which were built into the glass envelope. Typically he achieved 100 W at 25 cm with an efficiency of 25%. At the University of Hamburg, H. G. Möller investigated split-anode magnetrons both theoretically and experimentally as early as 1926 (Möller 1936). At the research institute of the German Post Office, H. Groos (1937) developed a two-vane split-anode magnetron operating at approximately 10 cm. At the same time,

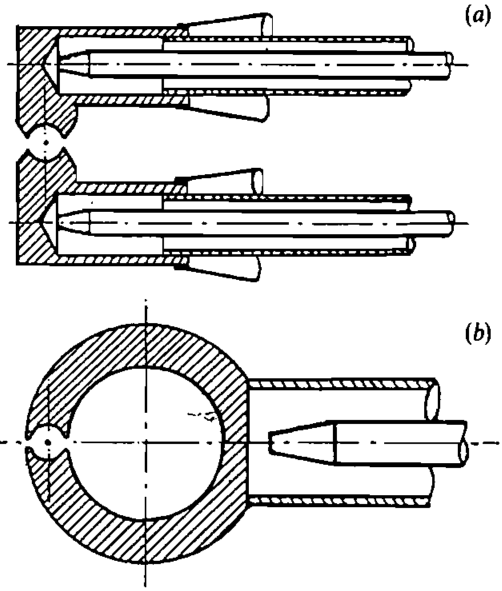

Figure 14. Water-cooled magnetrons (Pfetscher and Puhlmann 1936).

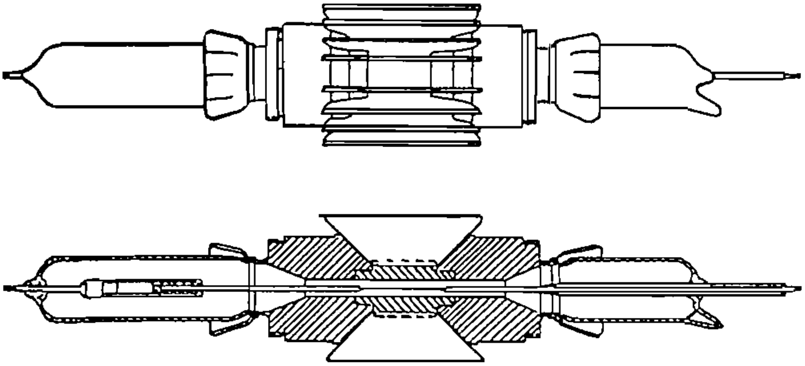

Figure 15. Single-anode magnetron (Mayer 1944).

the importance of a slight inclination of the tube axis relative to the magnetic field lines was also being discussed. Furthermore L. Müller (1941) reported the development of a magnetron suitable for amplitude modulation by applying a modulating voltage to a grid closely surrounding the cathode. He managed to obtain a 100% current modulation using very low modulating voltages.

At the Flugfunk-Forschungsinstitut FFO in Gräfelfing L. Mayer, an ingenious tube designer, developed several magnetrons and klystrons. In his work he was skillfully supported by a technological group under W. Knecht—jointly they developed, for example, a single-anode magnetron mounted inside a coaxial transmission line, tunable aver the range 2·6–12 cm and capable of delivering an output power of 50 mW–1 W (see Fig. 15). Using a somewhat similar water cooled tube they obtained an output of 10 W at 6 cm. In pulse operation a tunable continuous anode magnetron generated 600 W at a wavelength of 3·8 cm; a two-vane split-anode magnetron operating at 1·2 cm and delivering 100 mW CW should also be mentioned (Mayer 1944).

At Telefunken in 1938 several types of magnetrons were ready for use, for example one operating at 5 cm and delivering 1 W CW and another suitable for pulse operation and delivering 1 kW peak power at 20 cm (Fritz 1944). However some time afterwards a research engineer reported (Fritz 1980) that 'the company was a typical triode manufacturer and therefore demanded that all their tubes must be capable of amplitude modulation, external control and tuning'—consequently any further magnetron development was postponed in favour of the development of metal–ceramic triodes, all the more so since the military authorities had not yet recognized the advantages of microwave technology for radar applications. In 1940 the government finally put a stop to any research in the centimetre range. Soon afterwards some specialists in this field, particularly the theoreticians, were called up for active service.

The tubes that were available at the time were mostly multi-vane split-anode magnetrons whose anode sections were connected to suitable parallel-wire or parallel-plate transmission lines. As shown in Fig. 16 the transmission lines were either allowed to pierce the glass envelope of the tube or they were coupled capacitively to external transmission lines which could be adjusted in length. A typical example of such a tube was a six-vane split-anode magnetron RD2 Md which was manufactured in large quantities (Fritz 1944). This particular magnetron was developed before the war to operate at a wavelength of 5 cm, but it was later modified for the range 8–20 cm. It could produce 100–500 mW and only weighed 400 g, including its permanent magnet. The design of the tube is shown in Fig. 17. An approximately $3/8\lambda$ long transmission line is short-circuited on the left by a metal block which also carries the capacitively short-circuited cathode leads. The anode segments are placed at a distance of $\lambda/16$ from the short-circuited end of the line. The outer transmission line is capacitively coupled through the glass envelope. Such tubes had an indirectly heated cathode and worked in a constant magnetic field; when tuned using a shorting slide, they only required a small adjustment of the anode voltage. Thus they were widely used as local oscillators in search receivers. Owing to the war, a shortage of suitable materials caused all magnetrons to have to operate at the lowest permissible magnetic field (Gundlach 1948).

The most important tube, the multi-cavity magnetron, was already in existence in Germany in 1937. For example, Telefunken built an eight-cavity magnetron operating at 1·5 cm and capable of delivering 50 mW ouput CW. At Sanitas a water-cooled magnetron was developed to deliver 100 W CW at 25 cm. At this time, such tubes were called 'Radmagnetron' ('Rad' meaning 'wheel' in German). A tube developed in 1938 at C. Lorenz AG by F. Herriger for a wavelength of 8 cm is shown in Fig. 18. However the advantages of this particular design for pulse operation were not fully appreciated in Germany at the time.

In 1943 the situation changed quite radically when the use of very high frequencies became known owing to the above mentioned, so-called 'Rotterdamgerät'. An immediate interest in microwave frequencies was followed by a hectic period of development activity. The British magnetrons and reflex klystrons operating at 9 and 3 cm were first copied and then further developed. Thus at the end of the war Telefunken were able to manufacture magnetrons operating at 9·5 cm and delivering a pulse power of 1000 kW; at the other end of the spectrum they built a tube operating at 0·8 cm and delivering a pulse power of 1·5 kW. Two papers respectively by F. W. Gundlach (1948) and K. Fritz (1944) give additional information about magnetron development in Germany during the war.

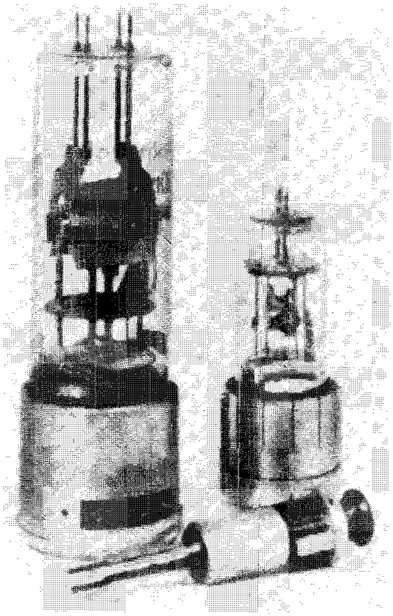

Figure 16. Two- and four-vane split-anode magnetrons.

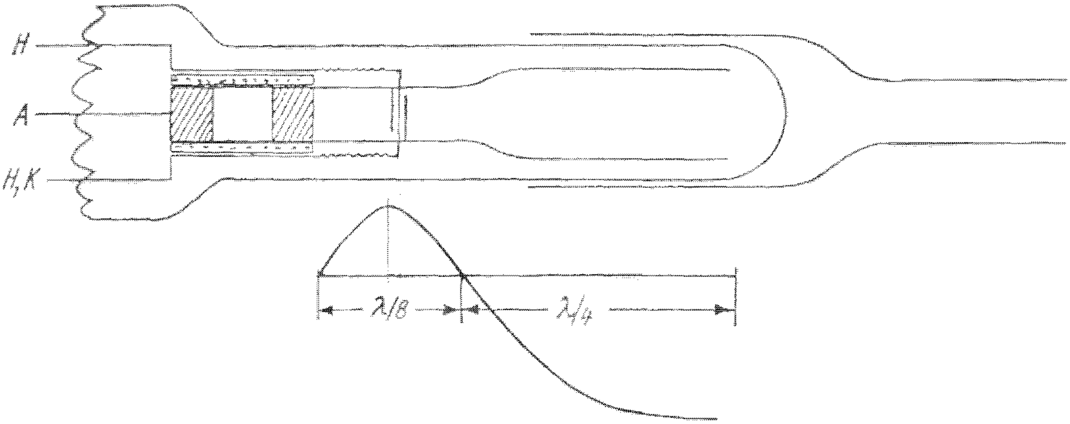

Figure 17. Schematic design of a six-vane split-anode magnetron RD2 Md. Below: voltage distribution in the resonant transmission line (Deutsche Luftfahrtforschung 1944).

3.3. *Klystrons*

This section should begin by mentioning Joh. Müller and his diode oscillator (Müller 1933). Müller in his doctoral dissertation submitted to the University of Munich was able to prove both theoretically and experimentally that a space-charge-limited diode is capable of generating oscillations in a parallel resonant circuit comprising the diode itself (for capacitance) and a simple wire loop (for inductance). In order to achieve this goal it was necessary to space the electrodes sufficiently far apart so that the conversion of a homogeneous electron flow into a density modulated flow, i.e. electron bunching (a feature of all transit-time tubes) can occur. In a space-charge-limited diode this corresponds to a static transit

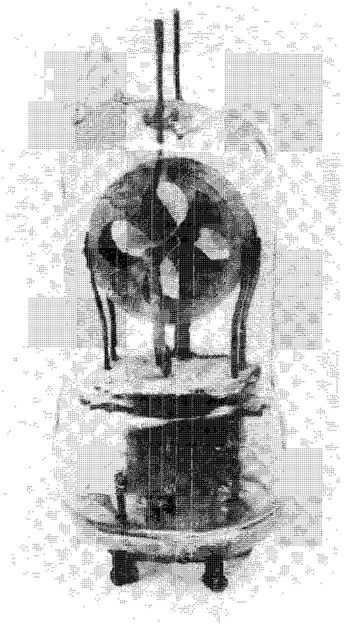

Figure 18. Four-cavity magnetron with a capacitively coupled output line, 1938 (C. Lorenz AG).

angle $\Theta \approx 7{\cdot}85$ rad; then the induced current has a negative real part which can compensate the usual circuit loss currents.

It would seem that the phrase 'phase focusing' was first used by B. Brüche and A. Recknagel (1938) to describe the situation when electrons traversing an alternating electromagnetic field reach a distant plane simultaneously, the analogy being between space focusing in optics and 'time focusing' in the case of electrons.

The next important contribution was made by Arsenjewa-Heil and Heil (1935). They described a transit-time tube in which the three characteristic features velocity modulation, phase focusing and energy transfer were designed to occur in three separate regions, an arrangement which is also characteristic of a klystron. Further they demonstrated, in my opinion for the first time, that it is necessary, in order to achieve high RF power output, to use a linear electron beam and that the beam must be positioned in such a way as to prevent the electrons from landing on RF electrodes—they must only be allowed to penetrate the fringe field of the electrodes, finally landing on a separate electrode, now called the collector. This arrangement made it possible to separate high frequency from beam guiding electrodes, thus permitted the use of high power electron beams. In 1935 the Heils also mentioned the possibility of efficiency enhancement by the use of a reduced (or step-wise reduced) voltage collector (Döring 1987), a technique which is now commonly used in high power tubes.

Almost immediately afterwards, the by now classical paper of R. H. Varian and S. E. Varian (1939) became available in Germany and klystron research was begun at several industrial and government research laboratories. However none of these investigations were in any way coordinated, since most of the activities had to be concealed. Such a state of affairs did not help in achieving speedy progress. For example the author, who from 1938 worked at the AEG Research Institute in Berlin, did not know who else was working in this field or what other institutes were involved in such work. Consequently only very few papers on klystrons were published and a proper survey of German research in this field is not feasible. A report prepared by F. W. Gundlach (1948) contains information on the more relevant publications which *did* appear in the period 1939–1945; here one can only mention some salient features of this work.

At the AEG Research Institute, L. Mayer (1939) provided an experimental proof of phase focusing in longitudinal fields, while the author was able to show experimentally the change in the velocity of electrons traversing the electric field set up by a pair of deflecting places (Döring 1939). The author also developed the two cavity klystron shown in Fig. 19, here still connected to the vacuum pump; in 1940 the klystron reached 100 W output at 30 cm (Döring 1988). In the same laboratory, E. Steudel extensively investigated the technology of copper–glass seals and later also designed two-cavity klystrons (Steudel 1942). After the author moved to C. Lorenz AG, H. Steyskal and L. Colani continued his work at AEG and built a sealed-off klystron; in its single resonator the drift space was in the form of a cylindrical tube supported by four spokes. Using this design they achieved, for short periods of time, 50 W output at 6·7 cm, the tube operating as an oscillator (Steyskal 1944).

L. Mayer (1942) at the Flugfunk-Forschungsinstitut FFO (Director M. Dieckmann) built a device very similar to a reflex klystron, but with a collector electrode which had a positive bias and acted as an emitter for a density modulated secondary electron beam. Noting the generated frequency of oscillation Mayer came to the conclusion that the emission time for secondary electrons must be shorter than 10^{-10} s. When operating with a negatively biased collector (i.e. a proper reflector), the water-cooled version of the tube delivered 8 W at 18 cm, when still on the pump. A sealed off tube, Fig. 20, provided with a resonator which was tunable with the help of a flexible diaphragm, was capable of delivering 60 mW over the range 3·5–5·5 cm. Mayer also investigated tubes with insulated reflectors and operation with a switched-off heater.

At the Deutsche Veruchsanstalt für Luftfahrtforschung in Berlin-Adlershof J. Labus and W. Dahlke (1942) as well as R. Hechtel (1944) carried out theoretical and experimental investigations of various problems associated with the operation of klystrons. In many laboratories in Germany, a great deal of time was spent on attempts to calculate klystron efficiency from the mean exit velocity of electrons in order to deduce the optimum tube dimensions for large-signal operation. In contrast, the Americans used simple approximate expressions for the electron velocities at the output of a buncher and rapidly obtained analytical expressions which proved to be very useful in the design of klystrons, although they were limited to small-signal performance only. Naturally there were no fast computers available at the time.

At the research institute of the Deutsche Reichspost, W. Reusse (1942) developed a two-cavity klystron generating 200 W at 30 cm; G. Goubau also described a klystron using a radial electron beam that did not require a magnetic field for focusing, but his design suffered from secondary emission problems (Goubau 1942).

All these developments were accompanied by various theoretical investigations.

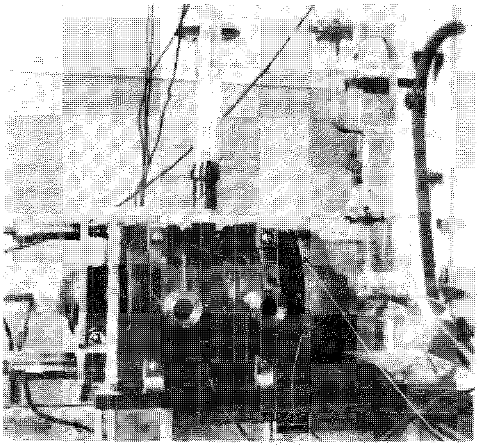

Figure 19. Two-cavity klystron, 1940 (AEG) (Döring 1988); tungsten spiral inside a Wehnelt cylinder acting as a simple electron gun on the right, water cooled hollow anode/collector on the left.

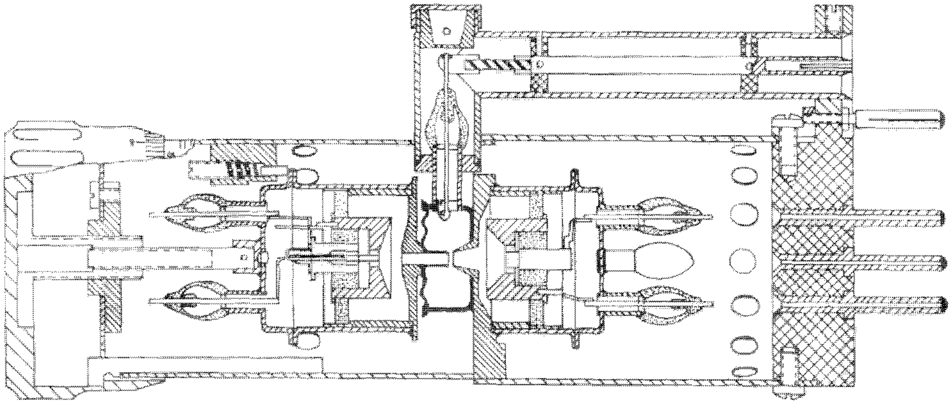

Figure 20. Reflex klystron for 3·5–5·5 cm waves (FFO) (Mayer 1942).

H. König working at Siemens and Halske developed a basic small-signal theory for velocity modulated transit-time tubes taking into account space charge (König 1943). F. Borgnis and E. Ledinegg (1940) have pointed out that klystron efficiency can be enhanced if one adds a resonator tuned to a harmonic and place it immediately behind the buncher. This arrangement leads to a much more efficient current density modulation and is widely used in present day high-power klystrons.

O. Heil who returned to Germany from Great Britain just before World War II broke out, joined the transmitting tube laboratory of C. Lorenz AG and

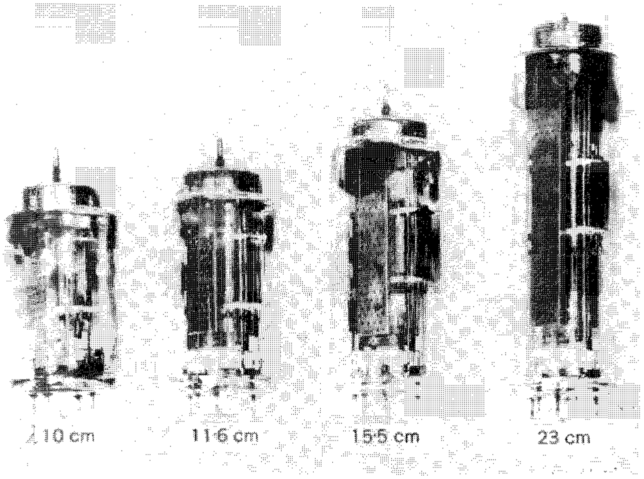

Figure 21. Heil-tube generators for four different wavelengths, 1941 (Herriger 1942).

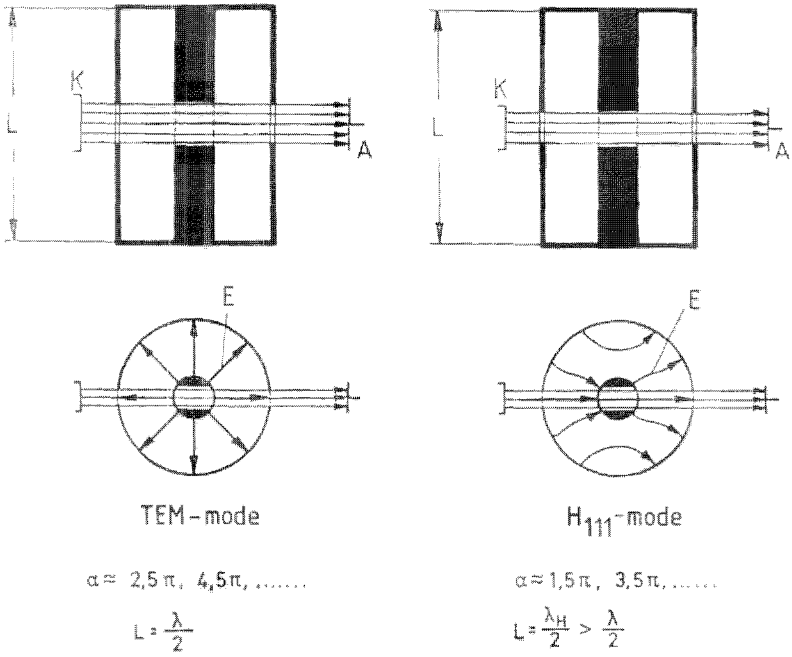

Figure 22. Two different modes of operation of a Heil-tube generator.

immediately started working on the development of klystrons with a single coaxial line resonator. Here a transverse electron beam is made to interact with the electric field where its value is a maximum, i.e. in a plane midway between the two short-circuited ends of the coaxial line. Assuming the existence of a TEM mode the tube can be called a 'one-circuit/two field klystron' whereby the electric field would oscillate 180° out of phase at the two ends of the beam (see Fig. 22). When Heil left the company the author continued his research by extending the range of frequencies (Fig. 21) the tube being originally designed to operate at 16 cm. Now

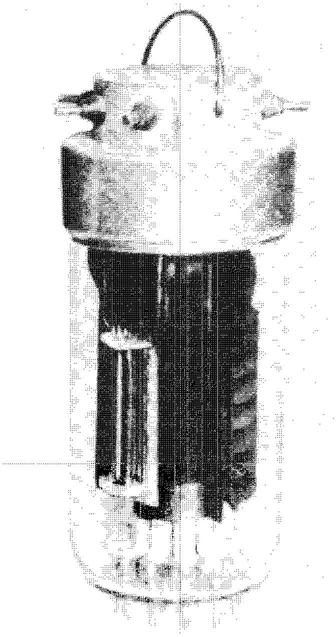

Figure 23. Tunable Heil-tube generator for 20–25 cm waves, RD12La, 1942 (C. Lorenz AG) Herriger 1942).

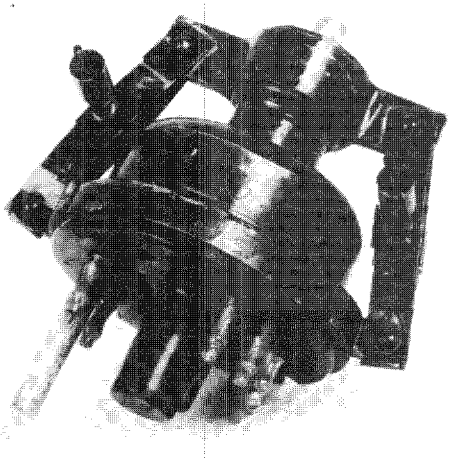

Figure 24. Reflex klystron LD20 (Telefunken) (Müller 1962).

the buncher and catcher gaps were chosen to have different dimensions in order to improve the tube efficiency (Döring 1944). When the resonator is allowed to oscillate in the H_{111} mode the electric field is in phase at both ends of the beam (Fig. 22); it is then possible to generate a new range of frequencies by adjusting the beam voltage. This particular mode of operation was also confirmed experimentally. The Heil tube could be tuned by short-circuiting the coaxial line at one end only, the other end being taken out through a glass base, as shown in Fig. 23; an external coaxial line with an adjustable short circuit can then be connected to the tube, the RF power being coupled out with the help of an inductive loop (Herriger 1942). In this case the base had twelve pins for the outer coaxial line conductor and four pins for the inner conductor, as shown in Fig. 4(*b*).

The tube was capable of generating oscillations in the waveband 18–50 cm and above. It was used in place of a magnetron in the radio link Stuttgart II, operating in the waveband 21·5–24·5 cm delivering 15 W of RF output power (as required by the specification for RD12 La). In the early days of manufacture, large variations in the maximum output power were experienced. K. Krebs investigated the problem and found that this was due to secondary emission of electrons in the catcher gap (Krebs 1950), the motion of secondary electrons in the strong field of the gap causing additional RF power losses; by altering the dimensions of the gap away from their optimal value for maximum RF power transfer the problem was partly cured, its effect being reduced to an acceptable level. Nowadays the dangers associated with the multipactor effect are well known to the designers of high-power klystrons. One should add that the RD12 La tube was the only klystron originally developed and fabricated in Germany during World War II; it was then used in the field as part of the appropriate radio equipment.

It had already been pointed out that an American reflex klystron was discovered in the so-called 'Rotterdamgerät' and it became the forerunner of the tube 723A/B. In the process of further development in Germany, its eccentric tuning mechanism was altered by the introduction of a double spring-leaf, as shown in Fig. 24; now the tuning mechanism was no longer asymmetrical, but the tube became much more difficult to operate! As in the case of the theoretical work, this clearly indicated different mental processes at work in the two countries. Further details concerning the development of the above tube can be found in the work of Müller (1962).

4. Concluding observations

This review is based on published papers, the author's own memories and personal acquaintance with many professional colleagues who were directly responsible for tube research and development. The author, himself a tube engineer of long standing, has attempted to describe the most important, fundamental and fruitful ideas in microwave tube research which originated in Germany. Most details concerning the more technological aspects of this work had to be omitted for reasons of space—consequently the survey is by no means complete. Furthermore, some developments could not be described either because there is no published record of them or because they were so confidential that the author knew nothing about them.

In retrospect the following trends can be noted: those places which had their own technological laboratory were at a marked advantage—this applied to most industrial research establishments and to the group at Gräfelfing; as the frequency of operation steadily increased, there was a natural move away from grid-controlled tubes towards transit-time devices, in spite of some ingeneous developments and encouraging results; again, as the frequency increased, transmission lines had to be replaced by cavity resonators in both types of tubes—they could then be made an integral part of the tube structure, eliminating the need for leads.

When working on this paper the author became aware of the valuable contribution to magnetron research by the staff of the Physikalisch-Technisches Institute of the University of Jena, first under Max Wien and W. O. Schumann and later under A. Esau. Not only was the Institute responsible for a number of important published contributions, but also quite a few talented students when working there received strong support early in their professional career. Moreover A. Esau when made responsible for high-frequency research during the war tried, if necessary by overlooking irksome regulations, to coordinate microwave tube research and thus help such experts as K. Steimel, who at the time was in charge of electron tube development and production.

A very comprehensive description of the development of microwave tubes in Germany until 1935 is given by H. E. Hollmann (1936). In a once secret report (Deutsche Luftfahrtforschung 1944) of a conference on electron tubes held in Breslau in 1944, up-to-date results of microwave tube research in Germany are clearly presented. Nearly all microwave tube engineers, including the author, were present at the conference. F. W. Gundlach, in a valuable report published shortly after the end of World War II, compiled the results of research investigations in the period 1939–1945, together with many original references (Gundlach 1948).

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