Description and Operating Characteristics of the Platinotron—A New Microwave Tube Device*

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Summary—**The term "platinotron" is the nomenclature given to a class of tube which, in general, comprises a circular, but nonreentrant, dispersive network matched at both ends over the frequency region of interest, and a reentrant electron beam originating from a continuously or nearly continuously coated cathode coaxial to the network. A dc potential is applied between the cathode and anode and a magnetic field is applied parallel to the axis of the cathode and transverse to the electric field between anode and cathode.**

In operation, the device works within the pass band of the network and exhibits directional properties, acting as an efficient, broad-band, saturated amplifier when the signal is passed through the device in one direction and as a passive network when the signal is passed through in the reverse direction. The platinotron has no region of linear amplification and may self-oscillate if the driving signal is removed. When the platinotron is being driven from an rf source, there is little or no power flow from the platinotron toward the driver. This behavior distinguishes the device from a conventionally locked magnetron oscillator.

Desirable characteristics of the platinotron include: efficiencies of 50 to 70 per cent; high peak and average rf power outputs, electronic bandwidths of 10 per cent with nearly constant efficiency over the entire bandwidth, low-phase pushing figure, low operating voltage, nominal gain of 10 db over a ten per cent frequency range, and a simple, compact mechanical structure.

Introduction

THIS PAPER describes a new device, the platinotron,[1] and some essential performance features of this device when used as a broad-band amplifier. The broad-band amplifier, or "amplitron"[2] application of this new device, helps fill the need for an efficient, high-power, broad-band amplifier for microwave radar.

The platinotron device has its roots in the magnetron. It is structurally similar to a magnetron and shares many of the essential circuit and electron beam interaction features of the magnetron. However, there are enough differences between the two to establish the platinotron as a device with radically different performance features. These new performance features include operation as a saturated amplifier over an appreciable band of frequencies of the order of 10 per cent, with high efficiency and a nominal gain of 10 db, without any mechanical or electrical adjustments of either the platinotron or the modulator power supply. In addition, the amount of phase shift between input and output is relatively insensitive to changes in the power supply. Efficiencies are in the range of 50–70 per cent and are, therefore, somewhat higher than for the conventional pulsed magnetron oscillator. The low insertion loss of the platinotron makes it possible to pass the signal received by the antenna back through the platinotron before entering the duplexer, thus permitting low-level duplexing. Relatively low operating voltages and simple mechanical construction are features shared with the magnetron.

Because of its close similarity to the magnetron in construction, it is surprising that the platinotron or a similar device has been so tardy in coming into being. It was well-known, for example, that the magnetron which was produced by the tens of thousands during World War II and which literally made microwave radar possible at that time, had a very broad-band circuit and that the circuit reentrancy was the cause of the narrow band of the device. There was indeed some modest effort expended in an attempt to make a more versatile operating device out of the conventional magnetron.[3] The failure of a greater effort to develop was probably caused by both the formidable analytical problems which made the magnetron approach unattractive to many investigators, and the publishing of attractive performance characteristics from an amplifier device[4] much more amenable to analyses. Another possible reason for the failure of the magnetron approach to mature earlier, was the failure on the part of engineers to recognize that there were important applications for a saturated amplifier of broad-band properties, quite independent of whether that device also had linear amplifier characteristics. The final emergence of the platinotron device then, is partly the result of persistence in forsaken fields and partly the result of a critical review of what performance characteristics were really fundamental and essential to a pulsed radar system.

The emergence of the platinotron may have significance other than its immediate usefulness as a broad-band amplifier: it may bring about a general consideration of reentrant beam tubes as a class. Reentrant beam tubes have a number of desirable characteristics such as high efficiency, compact size, etc., as well as presenting an opportunity for discovery of new properties.

Before proceeding further, it may be desirable to point out that the platinotron can be made into a highly frequency-stabilized self-excited oscillator by the addi-

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[1] The platinotron device is proprietary to the Raytheon Mfg. Co. The experimental data reported in this article were obtained under a U. S. Signal Corps contract.

[2] Trademark.

[3] Classified work sponsored by Bureau of Ships at Raytheon Mfg. Co., 1948–1950.

[4] R. R. Warnecke, W. Kleen, A. Lerbs, O. Döhler, and H. Huber, "The magnetron-type traveling-wave amplifier tube," PROC. IRE, vol. 38, pp. 486–495; May, 1950.

tion of rf feedback and the application of stabilizing circuits. The term "stabilotron"[5] has been assigned to this device. For a given degree of frequency stability much higher circuit efficiency can be obtained in the stabilotron than in a magnetron since the stabilizing cavity can be placed at the input to the stabilotron and hence absorbs less power. Improvement in frequency stability over a conventional unstabilized magnetron can range from 5 to 100 depending upon the category of frequency stability being compared; for example, whether the frequency-pulling figure or frequency drift due to temperature change is being compared. Although the properties and theory of the stabilotron are of considerable interest, they will not be discussed further in this article.

The material which follows is organized into five separate sections. The first section describes the platinotron device physically and compares it with the conventional magnetron oscillator. The second section discusses the characteristics of the device as a circuit element. The third section presents some detailed performance characteristics of the platinotron used as an amplifier. The fourth and fifth sections relate to general design considerations and their application to the QK434 platinotron.

The reader should keep in mind that while this article represents a sizeable release of information on the platinotron, it does not present a complete theory of the device, particularly with respect to the details of interaction between the circuit and the beam. Experimental data are incomplete with respect to performance lying in frequency regions outside a 10 per cent frequency band centered at 1300 mc.

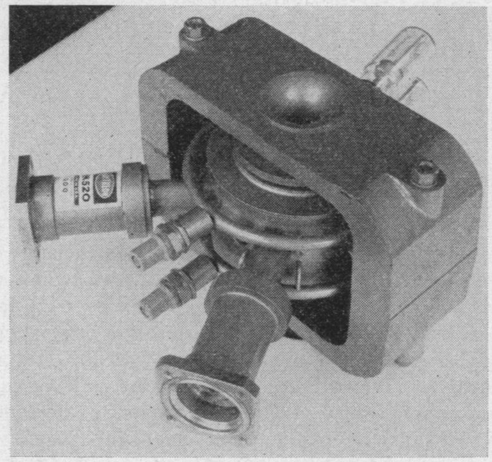

Fig. 1—Photograph of a platinotron and the permanent magnet used with it.

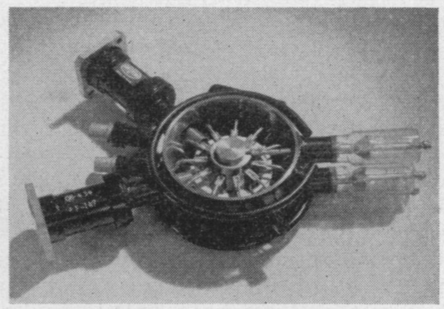

Fig. 2—Photograph of a platinotron with the magnet and one cover removed.

Physical Description of the Device

Fig. 1 shows the QK434, an L-band platinotron, with the external permanent magnet in place. Fig. 2 shows the same platinotron with the magnet and cover removed, exposing the internal circuit and cathode. Physically the device is similar to the conventional fixed frequency magnetron oscillator. Like the magnetron the electron beam is reentrant and originates from a continuously coated cathode which is coaxial to the rf circuit. Like the magnetron, the device is placed in operation by supplying a static magnetic field parallel to the axis of the cathode and an electric potential between the cathode and the rf circuit. But unlike the conventional magnetron oscillator, the rf circuit is nonreentrant[6] and the characteristic impedance of the rf circuit is matched at both ends of the circuit to two external rf connections over the frequency region of interest. This difference in the treatment of the rf circuit results in completely different operating behavior of the conventional magnetron oscillator and platinotron. The platinotron circuit treatment not only provides the two sets of terminals necessary for an amplifier, but it takes advantage of the natural broad-band characteristics of the rf circuit which the reentrant circuit treatment in the magnetron nullifies.

As shown in Fig. 3, the rotation of the space-charge cloud may be in either direction in the conventional magnetron oscillator without causing noticeable differences in performance, whereas in the platinotron, changing the direction of rotation relative to the input and output of the device will bring about a radical change in the behavior of the device.

Additional perspective as to the physical nature of the device may be obtained from Fig. 4 which gives a plan and cross section view of the QK434.

Characteristics of the Device as a Circuit Element

As a circuit element the platinotron may be best described as an active two-terminal-pair network with directional properties, as shown in Fig. 5. When an rf signal is injected into the first set of terminals, the rf level will be greatly increased at the second set of terminals. On the other hand, if the rf signal is injected into the second set of terminals, the rf level will be neither increased nor decreased at the first set of terminals. To a first approximation there will be the same phase shift θ_p of the rf signal as it traverses the device, regardless of

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[6] The cutting of the straps of a strapped platinotron circuit provides a high degree of isolation between the two circuit members thus formed.

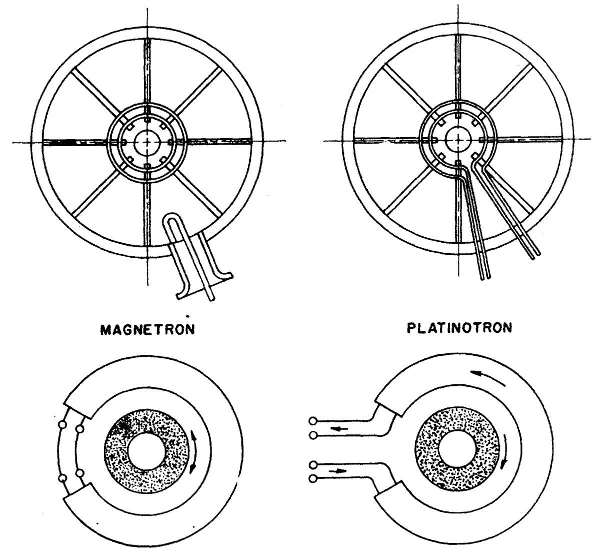


Fig. 3—Diagram illustrating the basic differences of construction and operation between the platinotron and the magnetron.

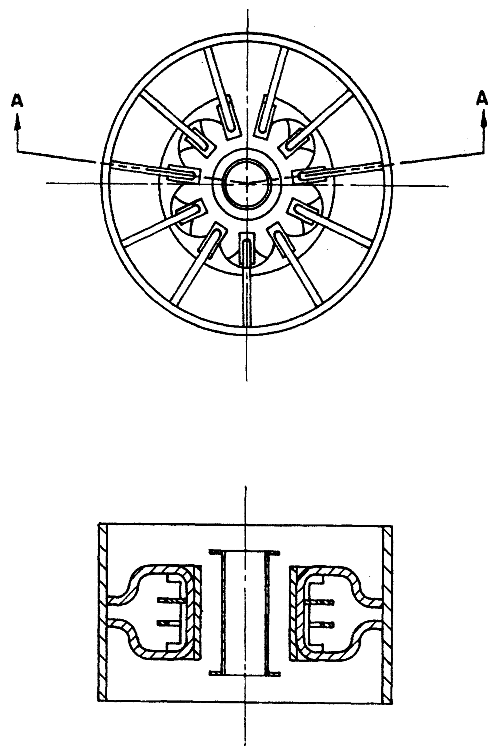


Fig. 4—Plan and cross section view of an *L*-band platinotron.

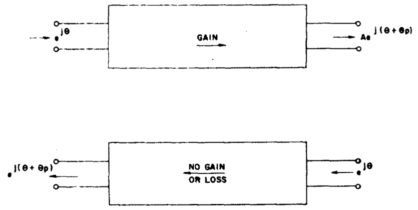


Fig. 5—The circuit element characterization of the platinotron.

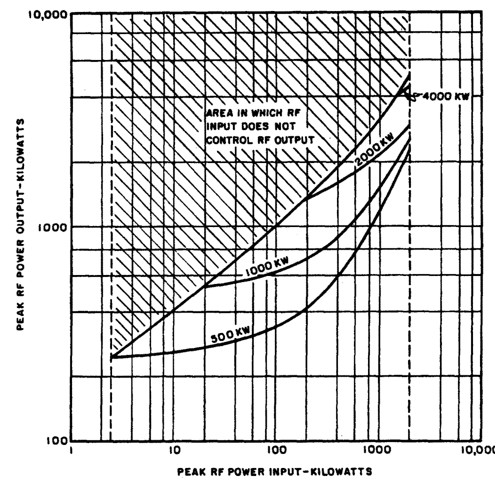


Fig. 6—The general relationship between the rf input and the rf output of the QK434 platinotron as a function of power input from the modulator.

direction. If the direction of the magnetic field is reversed, then the directional properties of the device are also reversed.[7]

Various performance characteristics of the device based on this simplified circuit concept can now be discussed. The first characteristic to be discussed is the relationship between rf input and rf output as a function of dc power input to the device. These characteristics for the QK434 are shown in Fig. 6. Quite clearly the device behaves as a saturated amplifier. For a given dc power input level, the rf output is relatively independent of the rf drive level, departing from this independence as the magnitude of the rf drive level becomes comparable to the rf output level, and as the rf drive level becomes so low that it loses control over the frequency of the rf output. In the region in which the rf input does not control the rf output, the rf output is noisy, poorly defined, and at some other frequency than the driving signal. The transition region between the controlled and uncontrolled areas is well defined and of negligible width.

The operation of the QK434 has been explored with rf drive levels as low as 2 kw to as high as 2000 kw. Over this range of driving signal, the curve marking the separation of the controlled and uncontrolled regions of operation has been found to be approximately

$$P_{o'rf} = 145(P_{i'rf})^{0.45}$$

where

$$P_{o'rf} = \text{rf power output in kw.}$$

$$P_{i'rf} = \text{rf power input in kw.}$$

This curve also determines the maximum gain that can be obtained at any rf drive level.

[7] The directional properties of the device may also depend upon the current level at which the device is operated. At very low current levels the QK434 has been found to have a forward-wave type of interaction, but at the current levels at which the QK434 would be operated as a power device, the beam-circuit interaction is of the backward-wave type. The shift occurs at a value of anode current of from two to three amperes.

$$\text{Maximum gain} = \frac{P_{o'\text{rf}}}{P_{i'\text{rf}}} = \frac{145}{(P_{i'\text{rf}})^{0.55}}.$$

As indicated in the above equation and Fig. 6, power gains of 20 db may be obtained at the lower drive levels, whereas gains of only a few db may be expected at the higher drive levels. It should be noted, however, that the rf input power is conserved in the rf output power, making it possible to use efficiently the higher power but lower gain levels of the platinotron.

The rf power which is generated within the platinotron flows predominantly out of the output set of terminals only. The fraction of the generated power which finds its way to the input set of terminals and appears at those terminals as reflected or reverse-directed power is only a small fraction of the output power of the device. This behavior is distinctly different from that associated with a conventionally locked oscillator with which the platinotron is occasionally compared. The ratio of the reverse-directed power to the output power for the QK434 is shown as a function of frequency in Fig. 7. If the reverse-directed power originates from a reflection at the output of the device, however, it passes back through the tube relatively unattenuated. The manner in which this device handles the power generated within it and the manner in which it handles reflected power from the output substantiates the circuit representation of Fig. 5.

A very interesting and useful property of this device is its ability to amplify, operate efficiently, and deliver large power output over a relatively wide frequency band. A typical plot of efficiency against frequency at a fixed power input level is shown in Fig. 8. The efficiency remains relatively constant over a 10 per cent or greater frequency band. At the time this article was prepared for publication the limitations on the bandwidth capabilities of the QK434 platinotron had not been determined because of the lack of a broad-band rf driver source. It seems reasonable to expect that the frequency dependency of the phase of the reentrant electrons relative to the wave propagating on the network will be a factor which will affect the performance over a band of frequencies, but it is not clear as to how and to what extent.

Another characteristic of this device of considerable practical importance is that the phase shift across the device is nearly independent of the dc current applied to the device over a relatively wide range of currents. The term "phase pushing" has been applied to the slope of the characteristic of frequency vs current because of its relationship to the term "frequency pushing" which is descriptive of a similar phenomenon in oscillators in which the frequency is changed or "pushed" as the current is changed. In the platinotron device the phase pushing can be measured either directly by noting the change in phase across the device as the current is changed, or it may be measured indirectly by using the platinotron as an oscillator and measuring the frequency change. In conventional magnetron oscillators, the frequency pushing can change from a positive value to a negative value, going through a zero value, as the current is increased. Similarly in the platinotron the "phase pushing" can obtain a value of zero. However, its value everywhere in the operating range is so low as to make quantitative measurements of phase pushing difficult. It has been necessary to note the phase change resulting from a relatively large change in current, and thereby obtain an average value of phase pushing over this current range. Fig. 9 has been prepared from such data. These data indicate that the phase pushing does go to zero and is everywhere small in value.

Considerably better data have been obtained on phase pushing by measuring the frequency pushing when the platinotron device is set up as a selfexcited oscillator, its frequency being primarily controlled by the relative position of reflections deliberately placed in the input and output. Such data are shown in Fig. 10 where it is clearly seen that the slope of the frequency vs current characteristic obtains a zero value for certain values of current and magnetic field. Since an oscillator in the steady state must always maintain a total loop phase shift of some integral multiple of 2π, and since the oscil-

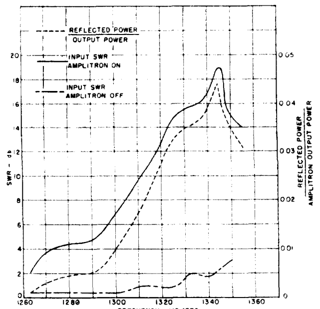


Fig. 7—Relationship between efficiency and frequency typical of platinotron performance.

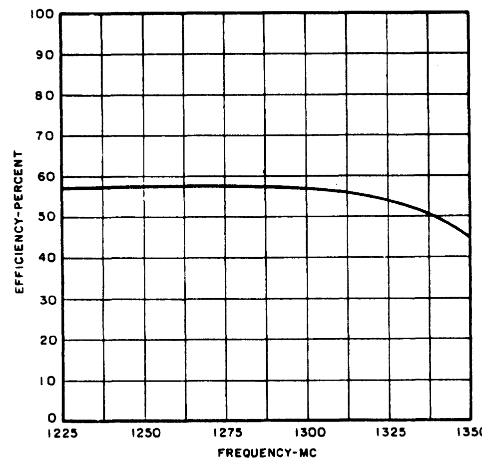


Fig. 8—Measurement of reverse-directed power at the input of the platinotron as a function of frequency with the platinotron operating into a matched load.

kv ↓ 1b →	10–20 A.	20–30 A.	30–40 A.
36	−0.8°/amp.	+0.34°/amp.	30–34 A. +0.85°/amp.
34.6	−0.45°/amp.	+0.22°/amp.	30–34 A. +0.8°/amp.
33.2	−0.44°/amp.	+0.22°/amp.	30–40 A. +0.9°/amp.
30.3	−0.6°/amp.	+0.40°/amp.	+0.8°/amp.
25.9	−0.8°/amp.	+0.60°/amp.	+0.9°/amp.

Fig. 9—Experimentally measured phase pushing characteristics in an *L*-band platinotron.

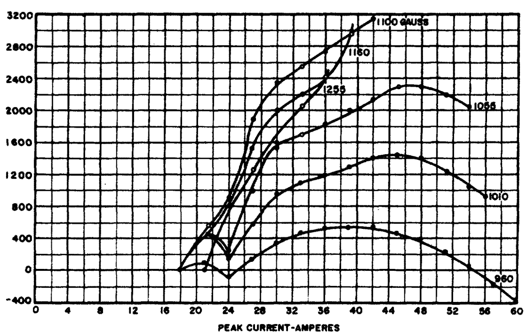


Fig. 10—Experimentally measured frequency pushing characteristics in an *L*-band platinotron operated as a nonstabilized oscillator.

lator is composed of elements whose phase shift is dependent upon frequency, a constant frequency can only be obtained if the phase shift remains constant. If the frequency of such an oscillator remains constant as the current is varied, the conclusion may be drawn that the phase shift also remains constant over the current region.

The possibility of obtaining zero or small phase pushing in an amplifier is of considerable significance in the design of many radar systems in which it is desired to hold the phase shift across the device constant while still making the modulator as simple and compact as possible.

The relationships between anode voltage, anode current, frequency, and magnetic field are of primary importance. These relationships are similar to those for a magnetron device, and will be developed later in this article. Representative data giving the relationship between anode voltage, anode current, and magnetic field, with the frequency held constant are shown in Fig. 11. The platinotron is a relatively low input impedance device, ranging from 500 to 1000 ohms depending upon the operating point which is selected.

Detailed Performance Characteristics of the Platinotron Used as an Amplifier—The "Amplitron"

Although the platinotron device itself has been described as an amplifier, it is possible to use it as a self-

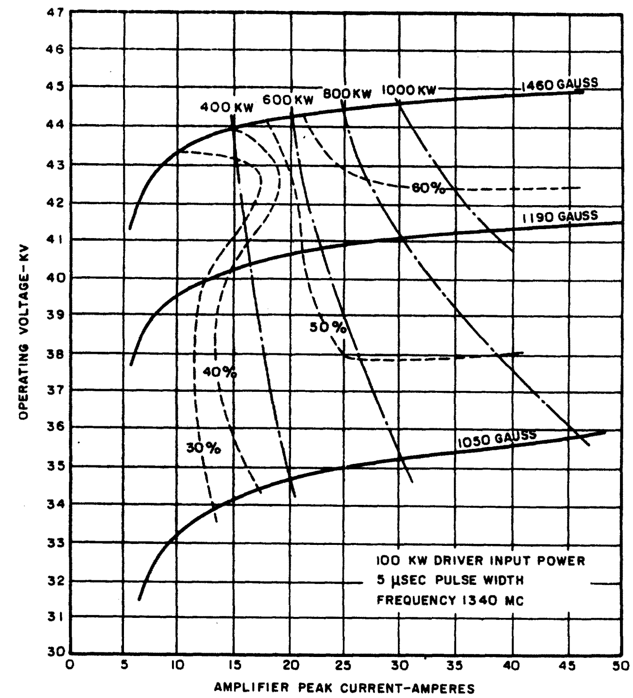


Fig. 11—Typical performance chart of an *L*-band platinotron (QK434). The relationship between anode current and applied anode potential for a particular value of magnetic field is given by the curves of constant magnetic field. Curves of constant rf power output and efficiency are shown.

excited oscillator, either stabilized or unstabilized. The term "amplitron"[8] has been assigned to the use of a platinotron in those applications where it is intended to drive it with an rf signal. The following material, therefore, describes the characteristics of the platinotron when it is used as an amplifier, and the term amplitron will, therefore, be used.

The Presentation of Amplitron Operating Data

In evaluating the performance of an amplifier, there is natural major concern as to the quality of the reproduction of the input signal. From the standpoint of evaluating the quality of reproduction, the usual ordinary measurements of efficiency, power output, gain, etc. are not enough. It is desirable to take each point of data in such a manner that a measure of the quality of the reproduction of the input signal is available. This is accomplished by photographing the input and output frequency spectra presented on a voltage basis on a spectrum analyzer. The voltage spectra are particularly useful as critical measurements, for the spectrum sidelobe structure is very sensitive to any reproduction change. As a further enhancement of critical evaluation, a relatively long pulse duration of 5 μsec is used. This results in a spectrum bandwidth of 400 kc between the first null points of the spectrum.

For amplitron tests, obtaining a good driver spectrum posed considerable difficulty. This problem was solved finally by using a stabilotron as the driver. Because

[8] Trademark.

spectrum analyzers of sufficient resolving power and stability were not generally available, a special analyzer was developed for the purpose of taking spectral data.

The amplitron tested was designated the QK520. Fig. 12 is a photograph of the actual amplitron test setup that was used. Fig. 13 is a schematic diagram of the amplitron test setup. Separate modulators for the driver and the amplitron were used but the trigger of one was slaved to the other. The times of the start of the two pulses and the pulse widths were made as nearly identical as possible. In the rf circuit, a resistive pad was inserted between the driver and the amplitron, primarily for the purpose of reducing the power output of the driver down to a usable input signal level for the amplitron. The pad served a second function in that it effectively isolated the driver from the amplitron. Such isolation is of particular importance when the amplitron is operated into a mismatched load.

The measurement of amplitron efficiency requires definition and discussion. In a nominal gain device where the input power appears as an appreciable percentage of the output power, a conservative definition of efficiency must make provision for the subtraction of this input power from the output power. Consequently, in all the data presented in this paper, the following conservative definition of efficiency is used:

$$\text{amplitron efficiency} = \frac{\text{rf power output} - \text{rf power input}}{\text{modulator power input to amplitron}}. \quad (1)$$

The definition of amplitron gain is, of course,

$$\text{amplitron power gain} = \frac{\text{power output}}{\text{power input}}. \quad (2)$$

Although the amplitron efficiency should be defined as above, it should be remembered that the input power is not lost but appears as part of the output power. The effective over-all efficiency of a chain of amplitrons can, therefore, remain very high.

In evaluating this device we must consider the effects of varying the parameters of anode voltage, anode current, magnetic field, level of rf drive, frequency of rf drive, and the load into which the tube operates. Over a very wide variation of these parameters the spectra reproduction should remain satisfactory throughout the region and not vary discontinuously in any manner. Therefore, the spectrum was photographed at frequent intervals of the parameters that were being varied.

Matched-Load Performance as a Function of Anode Current, Anode Voltage, Magnetic Field, Frequency, and Input RF Level

These data are presented in the same manner that magnetron data are often presented. The relationship between anode voltage and anode current is determined by the magnetic field strength, as indicated in Fig. 14

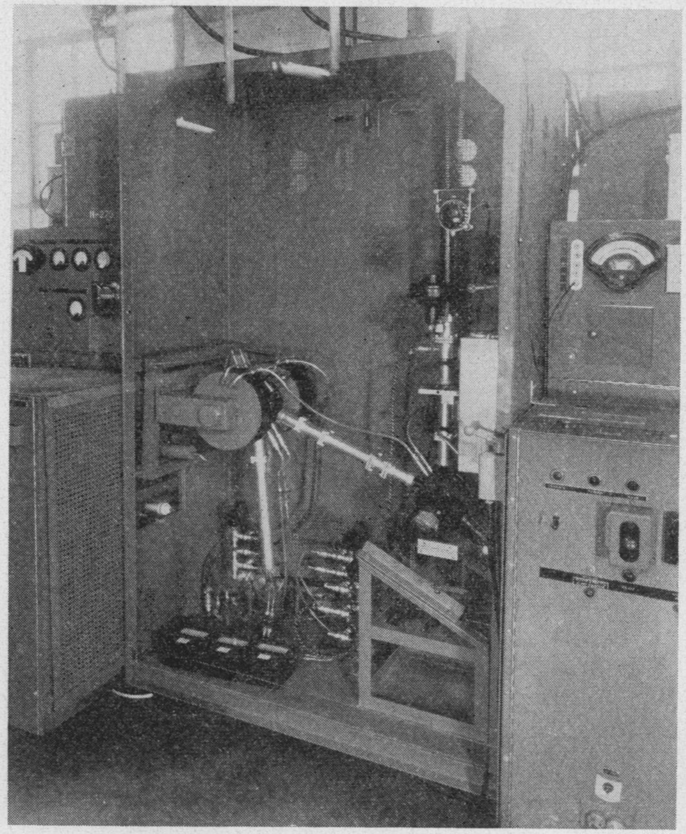


Fig. 12—Photograph illustrating the test setup for the amplitron. Stabilotron driver is on the right, the amplitron on the left surrounded by the test electromagnet.

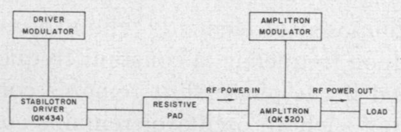


Fig. 13—Schematic diagram for the testing of the amplitron.

(opposite) by the three "Gauss" lines. The reproduction of the input spectrum is indicated at 5-ampere increments along each Gauss-line. Over the region of the graph in which spectra data are shown, the quality of the spectra is good and there are no regions of poor spectra. The highest current values, for which spectra are shown, mark the limits of amplification of the amplitron and indicate that good spectrum quality is maintained as the upper current boundary is approached. If the upper current boundary is exceeded, there is complete failure of amplifier action.

Power output, efficiency, and gain are shown below each spectrum photograph. The particular data shown in Fig. 14 and Fig. 11, which were derived from the data of Fig. 14, indicate increasing efficiency with increasing current and magnetic field. Efficiencies in the range of 60–65 per cent are attained.

These particular data were taken with an rf input power of 100 kw. Similar data taken at 10 kw and 50 kw of rf drive indicate no discontinuities of spectra quality over wide variation of the parameters of magnetic field

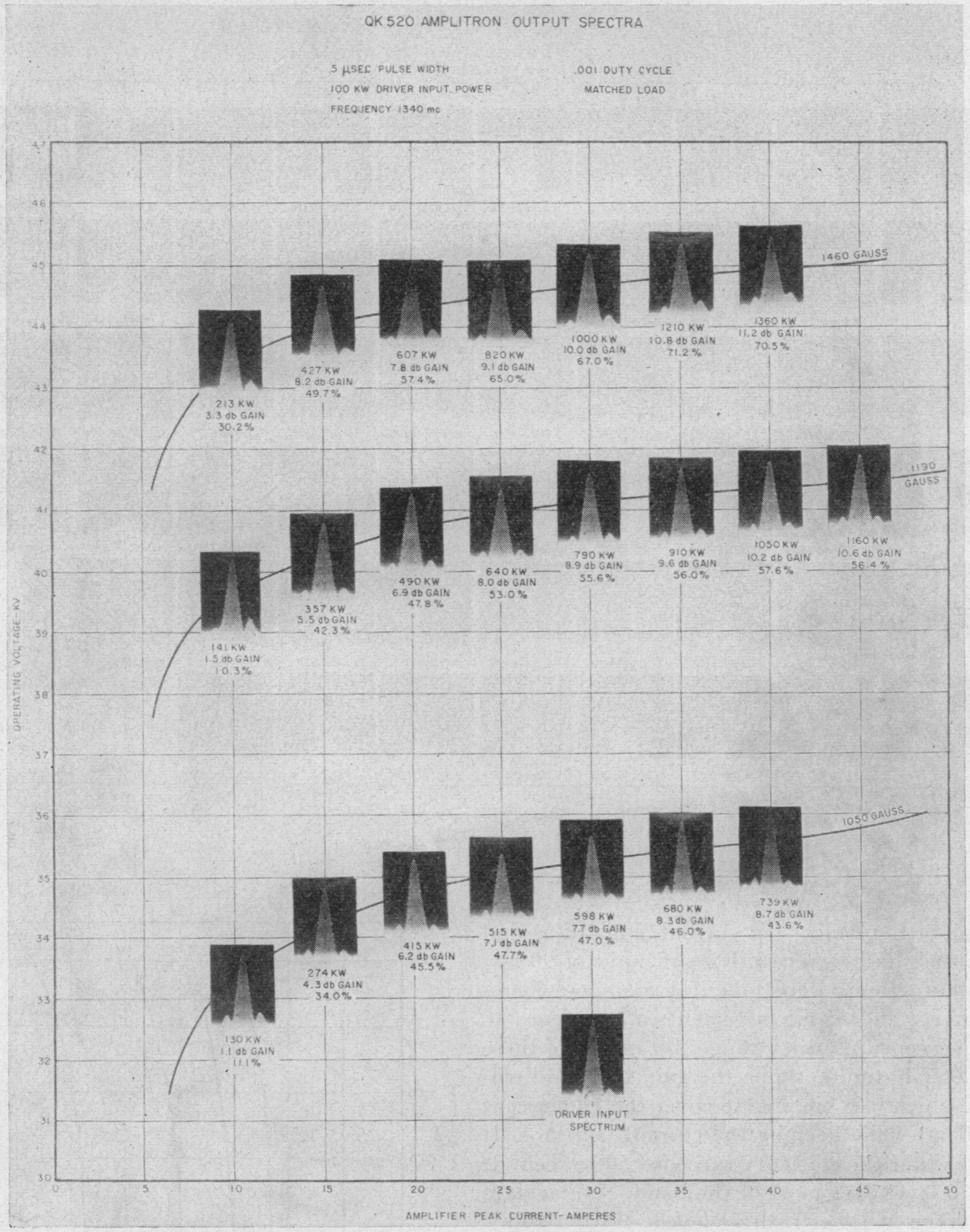


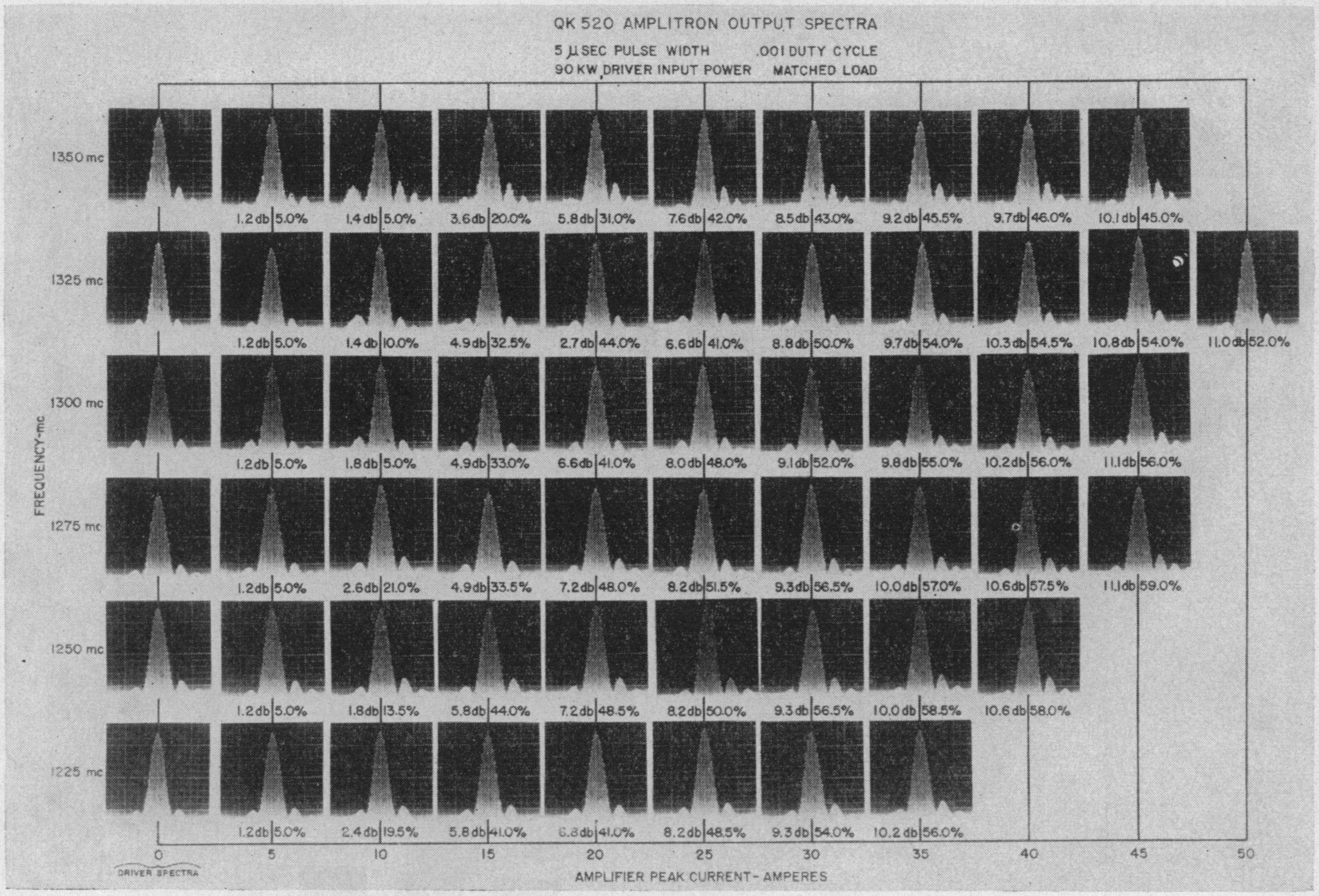
Fig. 14—Amplitron matched-load performance as a function of anode current, anode potential, and magnetic field at a frequency of 1340 mc and an rf drive level of 100 kw.

and current. With the higher drive power, higher peak powers as well as higher efficiencies are obtained, but the maximum value of gain is lower. With the lower values of drive power, the maximum gain values are as high as 16 db, but the maximum power output is greatly reduced. The increase in maximum gain and decrease in maximum power output with decreased rf input is characteristic of the QK520 *L*-band amplitron discussed in this paper and probably is characteristic of amplitrons in general.

The data discussed above were taken at 1340 mc. Similar data were taken at 1240 and 1290 mc and followed the same general pattern as that taken at 1340 mc.

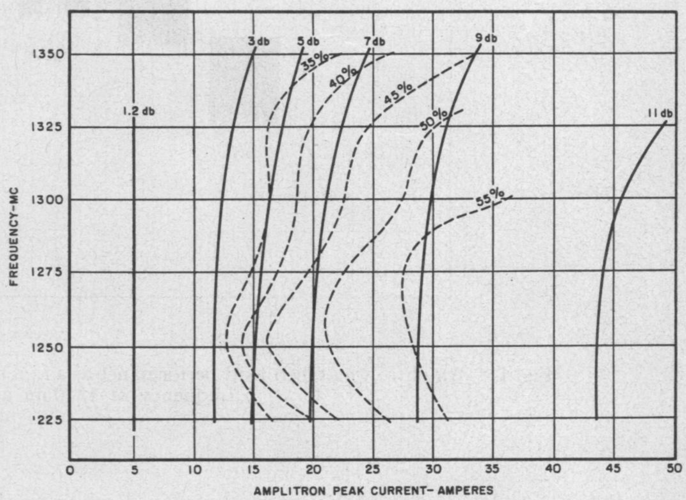
Matched-Load Performance as a Function of Anode Current, Frequency, and Input RF Level

A somewhat more instructive way of presenting data for the operating conditions which the amplitron will actually experience in service involves holding the magnetic field constant and examining the performance over



(a)

a wide range of frequency and current. Fig. 15(a) and 15(b) show such data taken with an rf input of 90 kw. Spectrum photographs were taken at 5-ampere increments of current and 25-mc increments of frequency to cover a 10 per cent frequency range. By means of these data it is possible to determine the gain level and efficiency with which it is possible to cover the 10 per cent frequency band while keeping the current constant. It may be noted that the efficiency exceeded 50 per cent at a 9.5-db gain level over most of the band. Similar data have been taken at lower rf drive levels. With a 10-kw drive level an amplification of 15.5 db with good reproduction over an 8 per cent frequency band was obtained.



(b)

Fig. 15—(a) Amplitron matched-load performance as a function of anode current and frequency at an rf input level of 90 kw and with the magnetic field held constant. Output spectra photographed at increments of five amperes of anode current and 25 mc of frequency. Output spectra at zero anode current is identical to input spectra. (b) Data of (a) replotted to indicate contours of constant efficiency and power output.

Variable-Load Performance as a Function of Frequency and Drive Level

To be practical, an amplifier must be capable of operating into a mismatched load of arbitrary phase and standing wave ratio of at least 1.5 in voltage and preferably higher. To examine the ability of the amplitron to meet these requirements, spectrum photographs and other essential data were taken for representative mismatches and plotted on load diagrams similar to that shown in Fig. 16. Spectra were taken for eight equally spaced phase positions of a 2.5/1 vswr and 1.5/1 vswr, and at the match point. The shape and quality of the spectrum varied a negligible amount under these varying conditions of load. The data of Fig. 16 are particularly interesting since the drive power of only 10 kw permits a gain of 16 db at the match point. The re-

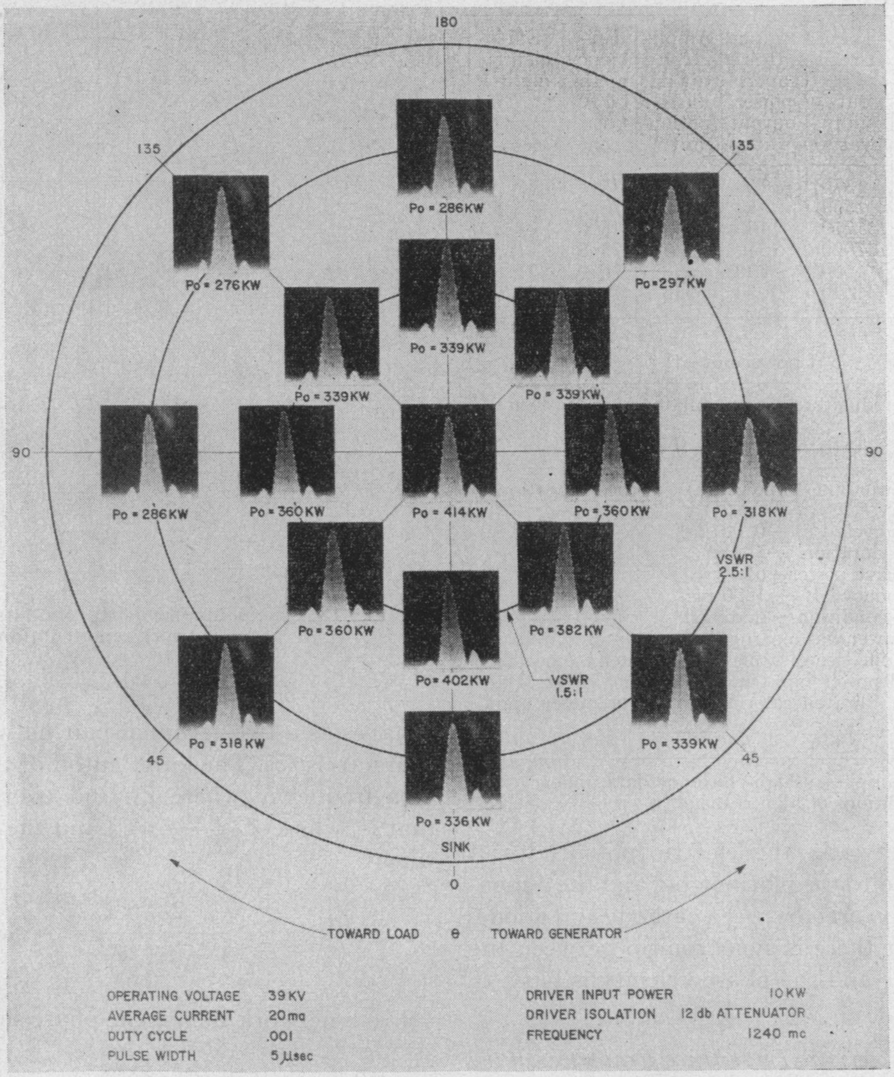


Fig. 16—Amplitron performance as a function of load at 1240 mc and with an rf input level of 10 kw.

flected power from a 2.5/1 vswr, therefore, represents a reflected power of over seven times the input power. The bulk of this reflected power is absorbed in the input pad between the driver and the amplitron. The data are of further interest in that they were taken at 1240 mc which is very near one frequency edge of the band. Similar data have been taken at 1290 mc and 1340 mc, respectively.

High-Efficiency Operation

The fact that all the input power appears in the output power of the amplitron, and is, therefore, not wasted, gives rise to consideration of the use of amplitrons at relatively low gains, if there is any practical benefit in doing so. For example, the paralleling of two tubes is often used as a device to double the power; it may be just as desirable to run two amplitrons in cascade to produce increased power although the gain of the second tube may be only 3 db.

Experimental study of high-level drive of the QK520 amplitron reveals that the advantages of extremely high efficiency and extremely high-power output are to be gained through high-level drive, low-gain operation of these tubes. Efficiencies of amplitrons run under these conditions were measured very carefully by the heat-balance method in which anode-dissipation power as well as output power are calorimetrically measured. These results were then checked against efficiency computed by the usual method of dividing the calorimetrically measured rf power output by the modulator power output. It was concluded that measured efficiencies were not less than 71.3 nor greater than 76 per cent for several operating conditions where the power exceeded 1600 kw. Observed data are tabulated in Fig. 17.

Design Considerations for the Platinotron

It has been determined that the QK434 platinotron in the power range where performance characteristics have been described, operates in a backward-wave mode, that is, there is interaction between a backward-wave space harmonic of the circuit and the rotating electron beam.

To examine this interaction quantitatively it is necessary to examine the relationship between the circuit

Magnetic field Gauss	Anode potential kv	Anode current ma	Total aver. power output watts	Amplitron aver. power output watts	Amplitron anode dissipation watts	Efficiency method A* per cent	Efficiency method B** per cent
1260	39	26	1370	760	312	75	71
1260	39.6	31	1560	950	356	77.5	72.8
1260	40.9	36	1710	1100	445	75.0	71.3
1260	42.7	41	1920	1310	535	75.5	71.3
1330	42.1	31	1600	990	338	76.0	74.5
1395	44.7	31	1640	1030	356	74.7	74.5

* Method A—efficiency = $\dfrac{\text{(rf power out} - \text{rf power in)}}{\text{(modulator kv) (modulator aver. current)}}$.

**Method B—efficiency = $\dfrac{\text{(rf power out} - \text{rf power in)}}{\text{(rf power out} - \text{rf power in)} + \text{anode dissipation}}$.

Conditions of operation
- Duty cycle —0.001
- Pulse duration —5 μsec
- RF drive power—610 kw
- Frequency —1300 mc
- Load condition —matched.

Note: Input drive power was measured at output of amplitron with amplitron turned off. Use of same power meter to measure both power output and power input minimized any effect of an error in the carefully calibrated calorimetric power meter upon efficiency.

Fig. 17—QK520 amplitron high-efficiency data under conditions of high rf drive.

properties of the network, the electric potential and magnetic field applied to the platinotron, and the dimensions of the interaction area between cathode and anode. The assumption that there is synchronism between the rotating space-charge and the phase velocity is basic to this relationship.

The Phase and Characteristic Impedance Properties of the Platinotron Circuit

The phase shift vs frequency characteristic of the platinotron is necessary in the determination of the phase velocity of the space harmonic interacting with the electrons. But in the examination of the circuit for this characteristic, it will be convenient to discuss the characteristic impedance of the platinotron circuit as well. The strapped structure, common in magnetrons and in many of the platinotron structures which have been built, will be discussed, with the full realization that similar expressions can be developed for other structures.

Fig. 18 shows a section of the strapped circuit. If we regard the two straps as a parallel transmission line with the platinotron cavities representing impedances hung across the transmission line as loading, we obtain an equivalent circuit as shown in Fig. 18, where L_S represents the strap inductance between cavity sections, C_S the capacity between the two straps, and Z_C, the input impedance to the cavity across the points of strap connection, for example, points A-D. Z_C may be considered as nearly purely reactive. This equivalent circuit

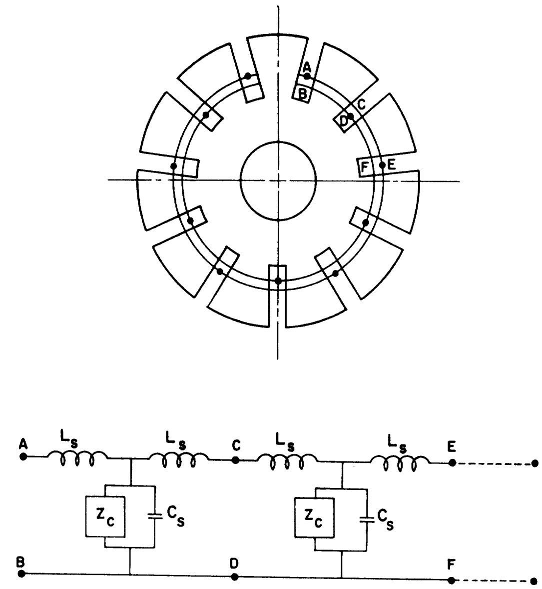


Fig. 18—The platinotron circuit and its two-terminal-pair network representation.

behaves as a two-terminal-pair network with band-pass characteristics. The lower cutoff of the pass band occurs at a frequency where Z_C and C_S resonate in parallel, that is, where $Z_C = -j/\omega C_S$ and the upper cutoff occurs when

$$\frac{2Z_C}{1 - j\omega C_S Z_C} = -j\omega L_S.$$

From network theory the phase shift function is given as

$$\theta_p = \cos^{-1}\left(\frac{Z_{11}}{Z_{12}}\right) = \cos^{-1}\left\{\frac{j\omega L_S + \dfrac{Z_C}{1 - j\omega C_S Z_C}}{\dfrac{Z_C}{1 - j\omega C_S Z_C}}\right\} \tag{3}$$

$$\theta_p = \cos^{-1}\left\{\frac{j\omega L_S}{Z_C}\left[\left(1 - \left(\frac{\omega}{\omega_c}\right)^2\right)\right] + 1\right\} \tag{4}$$

where ω_c is defined as the lower cutoff frequency, that is, $\theta_p = 0$. The characteristic impedance function is given as

$$Z_p = \sqrt{Z_{11}^2 - Z_{12}^2} \tag{5}$$

$$Z_p = \sqrt{j\omega L_S\left(j\omega L_S + \frac{2Z_C}{1 - j\omega C_S Z_C}\right)}. \tag{6}$$

The phase shift and the characteristic impedance functions are shown in Fig. 19 for a particular choice of circuit parameters in which Z_C is assumed to consist of a

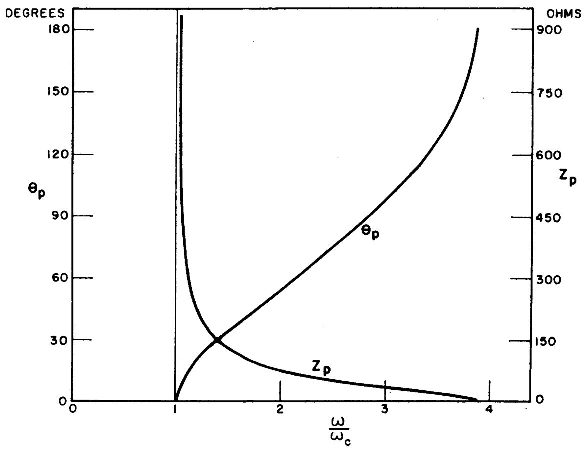


Fig. 19—Theoretical phase shift and characteristic impedance functions typical of the network representation of Fig. 18.

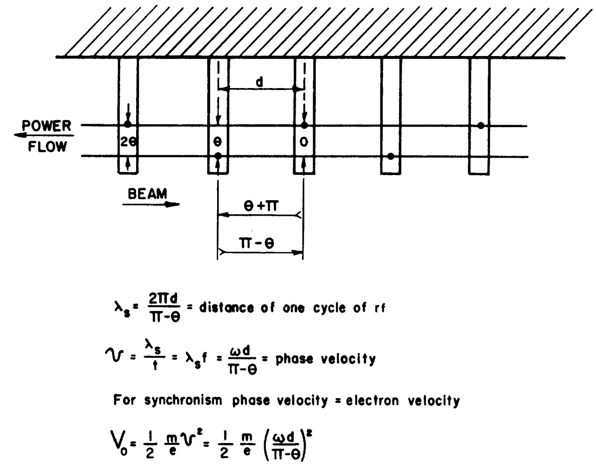


Fig. 20—Diagram illustrating conditions for interaction of the beam with a wave traveling in a direction opposite to that of the beam.

lumped inductance and capacity. In general Z_C will not be a simple function of frequency.[9] The phase shift across the network will be zero at the lower cutoff frequency and π radians at the upper cutoff frequency. There will usually be a substantial range in which the phase shift is nearly linear with frequency. The characteristic impedance is infinite at the lower cutoff frequency and zero at the upper cutoff frequency.

Conditions for Synchronism Between the Circuit Wave and the Electron Stream

Having obtained the phase shift θ_p as a function of frequency for the network, it is possible to investigate the synchronism relationship between the electron beam and the traveling wave on the circuit. Fig. 20 indicates a section of the network in which the direction of power flow in the circuit is indicated as being toward the left and the direction of the beam toward the right. The reversed directions of electron motion and power flow in the circuit are necessary conditions for backward-wave interaction. The phase shift per network section, as given by (4) is in the direction of power flow. This phase shift is along the straps. To convert this to a phase shift in the interaction area it is necessary to add or subtract π radians because of the manner in which the vanes are connected to the straps. Since θ_p is always less than π, the subtraction of π radians from θ_p will mean a phase shift in the interaction area in the direction of the beam.

If d is the distance between vane tips, then

$$\lambda_S = \frac{2\pi d}{\pi - \theta} = \text{distance of one rf cycle} \tag{7}$$

$$v = \frac{\omega d}{\pi - \theta} = \text{phase velocity.} \tag{8}$$

[9] Suitable expressions of Z_C for some common tube geometries are given by G. B. Collins, "Microwave Magnetrons," McGraw-Hill Book Co., Inc., New York, N. Y., pp. 49–65; 1948.

Then for synchronism the electron velocity must match the phase velocity and we have

$$V_0 = \frac{1}{2}\,\frac{m}{e}\left(\frac{\omega d}{\pi - \theta}\right)^2 \tag{9}$$

which gives the voltage through which the electrons must be accelerated to reach the required velocity.

Interrelationship of the Magnetic Field, DC Potential Applied to the Anode, and Physical Dimensions of the Interaction Region—Design Equations

In order to interrelate the magnetic field, dc potential applied to the anode, and platinotron physical dimensions, the assumption is made that there will be no interaction until synchronism between the traveling wave on the circuit and the fastest moving electrons is reached, and that further interaction will be maintained at such synchronism. However, it is not at all necessary for the electrons to be located at the tips of the vane for effective interaction and, for efficiency considerations, it is quite necessary that the synchronism condition be established early in the movement of the electron from the cathode to the anode. Eqs. (10)–(12) relate the voltage at which operation begins to the physical dimensions of the tube and value of magnetic field. These equations will be recognized as being similar to the design equations for magnetrons with the difference that $N(\pi-\theta)/2\pi$ has been substituted for the mode number n.

$$V = V_0\left(2\,\frac{B}{B_0} - 1\right) \text{ volts} \tag{10}$$

$$V_0 = 253{,}000\left[\frac{2\pi r_a}{\dfrac{N(\pi - \theta)\lambda}{2\pi}}\right]^2 \text{ volts} \tag{11}$$

$$B_0 = \frac{21{,}200}{N\left(\dfrac{\pi - \theta}{2\pi}\right)\lambda\left[1 - \left(\dfrac{r_c}{r_a}\right)^2\right]} \text{ Gauss} \tag{12}$$

where

V = threshold voltage or where operation starts,

V_0 = value of voltage between anode and cathode, which, with a field of B_0, causes the electrons to just graze the anode at synchronous velocity,

B_0 = value of magnetic field for grazing of anode by electrons at synchronous velocity,

B = value of magnetic flux in Gauss,

r_a = radius of anode in centimeters,

λ = operating wavelength of tube in centimeters,

N = number of vanes (assumed equally spaced),

θ = phase shift along straps of the network as defined in (4).

If the reader is not familiar with the principle of operation of the magnetron, he is advised to refer to one of the books[10] which treats this subject. Inclusion of such material here would only be repetitious.

Limitations on Bandwidth Caused by the Electron Reentrancy

The platinotron may not operate equally well at all values of θ because of the electron reentrancy involved. Consider, for example, attempting to operate an odd numbered vane platinotron in the π mode. Fig. 21 should make it clear that in the π mode ($\theta = 0$) electrons which are bunched to deliver energy to the traveling wave at the input of the network will take energy from the traveling wave at the output of the network after traversing the gap between input and output. Such a situation may not be conducive to a satisfactory interaction between electrons and a circuit traveling wave, although it is conceivable that the unfavorably bunched electrons could regroup themselves and move into a region of favorable phase.

On the other hand, if there is approximately 180° phase shift along the straps from output to input, the bunched electrons will deliver energy to the circuit on either side of the gap between output and input. This situation is favorable to the proper operation of the platinotron.

The general requirements for the electron bunches to be in phase with the traveling wave on both sides of the gap can be derived. Consider a bunch of electrons located at the output plane shown in Fig. 21 at time $t = 0$. Then if t' is the time required for this group of electrons to rotate around the cathode once and come back to the output plane, the phase change at the output plane is obviously $\omega t'$. And, of course, if the electrons and the traveling wave are to have the same phase relationship at t' as at $t = 0$, $\omega t'$ must be an integral multiple of 2π.

$$\omega t' = M 2\pi, \text{ where } M \text{ is an integer.} \tag{13}$$

[10] *Ibid.*

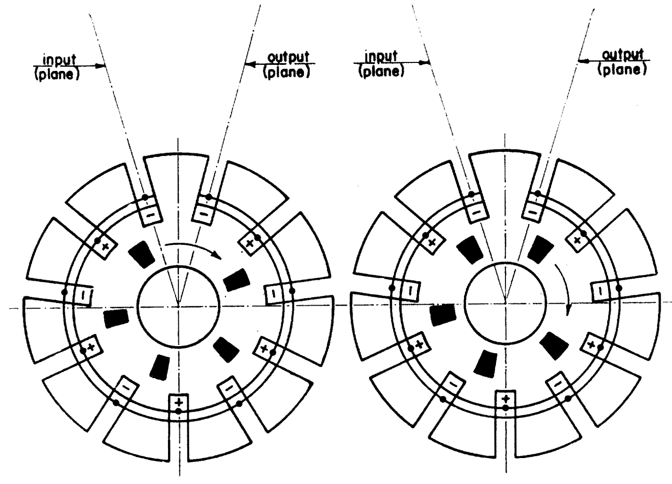


Fig. 21—Diagram illustrating poor conditions for interaction of the spokes of space-charge with the platinotron circuit.

Now t' is equal to the distance around the anode divided by the velocity of the electron bunches. This velocity is the phase velocity V given by (8). Then

$$t' = \frac{2\pi r_a}{v} = \frac{2\pi r_a}{\dfrac{\omega d}{\pi - \theta}} = \frac{N(\pi - \theta)}{\omega} \text{ secs.} \tag{14}$$

Substituting the expression for t' into (13) we obtain

$$\theta = \pi\left(1 - \frac{2M}{N}\right) \text{ radians.} \tag{15}$$

If the electrons after crossing the gap are permitted to initially lead or lag the traveling wave on the circuit, additional equations may be derived to determine the corresponding phase shifts permitted on the network.

$$\theta_{\max} = \pi\left[1 - \frac{2(M - Q)}{N}\right] \tag{16}$$

$$\theta_{\min} = \pi\left[1 - \frac{2(M + Q)}{N}\right] \tag{17}$$

where

$$Q = \frac{\text{lead or lag of beam in degrees}}{360}.$$

Application of the Circuit, Synchronism, and Bandwidth Aspects of Platinotron Design to the QK434

The QK434 is the experimental platinotron developed under Signal Corps contract. It was designed for use at L band and for a peak output power level of 200 to 1000 kw. A considerable amount of data have been taken on the use of this tube both as an amplitron and a stabilotron. It is, therefore, logical to use this tube to illustrate various aspects of platinotron design and performance.

A plan and cross section view of the interaction area of the QK434 platinotron is shown in Fig. 4. Pertinent dimensions are as follows:

Number of vanes $=11$
Cathode diameter $=0.750$ inches
Anode diameter $=1.600$ inches
Vane length $=1.500$ inches.

The experimental phase shift vs frequency curve for the entire network of ten cavities of the configuration shown in Fig. 4 has been found to be as shown in Fig. 22. The formula given by (4) for a single network section is difficult to apply for vanes of this geometry because of the difficulty of determining Z_C as a function of frequency. If, however, Z_C is assumed to be the impedance of a lumped circuit element, which must be inductive in nature, it is possible to compute the value of L_C using the experimental lower cutoff frequency and one other point from the 1200–1400 mc region of the phase shift vs frequency characteristic. If the values of ωL_C so obtained are then used for Z_C in (4), the agreement between the experimental curve and that predicted by (4) will be excellent in the frequency region up to 1500 mc. Beyond this frequency, however, there is serious lack of agreement.

With the aid of the phase shift vs frequency characteristic given in Fig. 22, it is possible to apply (15)–(17) to determine the preferred frequencies of operation. The results are shown in Fig. 23. Eq. (14) may be solved for the values of the phase shift across each network section which will permit the reentrant electron beam to reenter the input side of the circuit in exact synchronism with the circuit wave. These values of phase shift are found to be 17° and 49° and higher values not shown in Fig. 23. The platinotron will operate satisfactorily at either of the two frequencies determined by the two respective phase shifts. Fig. 23 also shows in heavy shading the frequency regions determined by (16) and (17) for a 45° lag and lead of the reentrant beam, and in lighter shading the frequency regions determined by a 90° lag and lead of the reentrant beam.

It is not clear from an examination of Fig. 23 whether operation at 800 or 1300 mc is to be preferred. Because the 1300-mc region represents a frequency region of interest to radar systems, most of the experimental data have been taken in this frequency region of operation, although very efficient operation has been observed in the 800-mc region.

From the dimensions given for Fig. 4, from the phase shift and frequency as determined by (4) and Fig. 22, and from (10)–(12), it is possible to determine the relationship between anode potential and magnetic field

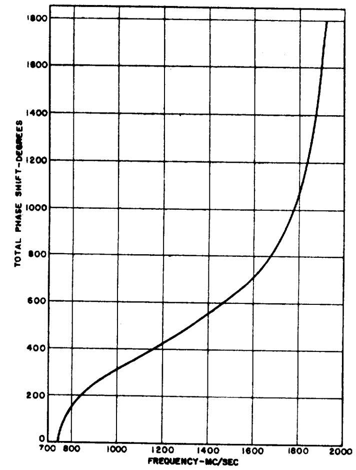


Fig. 22—Experimentally determined phase shift across the QK434 platinotron network of ten sections as a function of frequency.

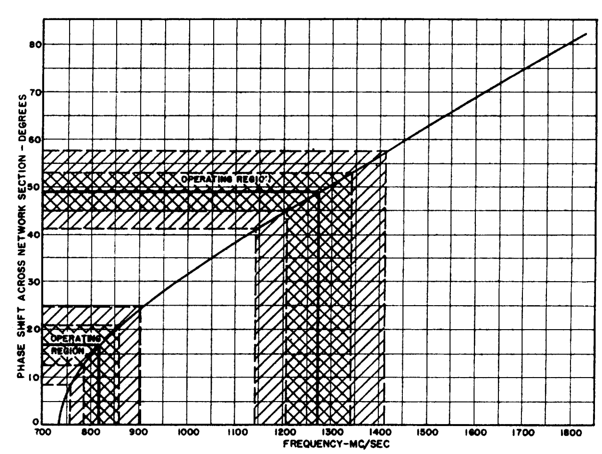


Fig. 23—Diagram illustrating regions of phase shift and frequency in which operation of the QK434 platinotron may be expected. Heavily cross-hatched regions correspond to a 45° lead or lag of the rotating spokes. Lightly cross-hatched regions correspond to a 90° lead or lag.

for the onset of operation for backward-wave interaction. The relationship between this threshold voltage and the magnetic field for a frequency of 1300 mc is given as the upper curve in Fig. 24. The lower curve in Fig. 24 indicates the predicted relationship between anode potential and magnetic field for interaction with the forward wave at 1300 mc. Eqs. (10)–(12) can be converted to predict forward-wave interaction by adding θ to π in the equations instead of subtracting it.

In the region of rf input levels over 2.5 kw, the experimentally observed values of threshold voltage appear in substantial agreement with the predicted values for backward-wave interaction. The range covered by these experimental data is also indicated on Fig. 24, However, at lower rf input levels forward-wave interaction has been observed at current levels from zero to 3 amperes.

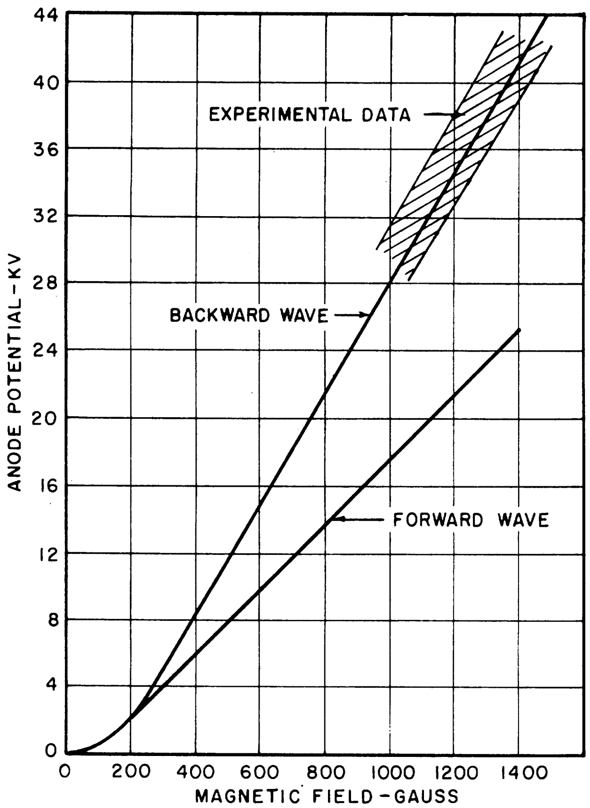


Fig. 24—Theoretically predicted and observed relationship between anode potential and magnetic field for onset of QK434 platinotron operation. Cross-hatched area contains points of experimentally observed behavior.

The proper operation of the platinotron is dependent upon a reasonable impedance match between the platinotron network and the input and output terminals over a reasonable range of frequency. For suitable tube geometries (6) may be used to compute the characteristic impedance. For the QK520 the characteristic impedance at 1300 mc was experimentally found to be 92 ohms. Although considerable work has been expended on the matching problem, such problems are common to a variety of microwave tubes, and so need not be discussed in detail here. The broad-band match, which was obtained for the QK520, is shown in Fig. 25. The vswr

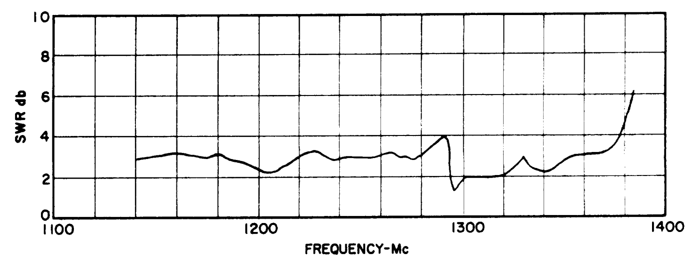


Fig. 25—Broad-band match between the external circuit and the QK434 platinotron.

as given in Fig. 25 is that vswr obtained by looking into the input to the platinotron with the output pipe looking into a matched-load.

Conclusion

A new microwave tube device has been described and a significant amount of data has been given to illustrate its major performance characteristics. Some information relative to design procedures has been given. All the data which has been presented is for a backward-wave mode of interaction, but this does not preclude the use of this device in a forward-wave interaction mode. Such forward-wave interaction has been noted at low rf drive levels and low anode currents.

The mechanism of interaction between the beam and circuit is not fully understood because of the complications of considering both electron reentrancy and circuit nonreentrancy simultaneously. A fuller understanding is essential to the prediction of the bandwidth and gain capabilities of this device. It is expected that analytical and experimental work in process will provide greater understanding of the beam-circuit interaction mechanism.

Acknowledgment

The author gratefully acknowledges the support given this development by the U. S. Signal Corps, whose support greatly accelerated development of an embryonic device into a practical device whose major characteristics and potentialities are now well recognized.