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Mechanism of Barkhausen-Kurz oscillations

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UMI
MECHANISM OF BARKHAUSEN-KURZ OSCILLATIONS

BY

Lumir Frank Dytrc

A Thesis Submitted to the Graduate Faculty for the Degree of
DOCTOR OF PHILOSOPHY
Major Subject: Applied Physics

IOWA STATE COLLEGE
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Iowa State College
1933
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X. INTRODUCTION

The trend in radio communication has been toward operation on the shorter wave-lengths. At first, the simpler apparatus with its more efficient utilization of a given radiating system directed the movement. Later, the congested states caused by large numbers of stations operating within rather narrow wave-limits were instrumental in sustaining this tendency. At the present time, utilization of the short wave-lengths appears more imminent than ever.

One thing favoring the use of short waves is the fact that the amount of power radiated becomes greater as the wave-length is shortened. Approximate formulae for radiation resistance indicate that it varies directly as the square of the height of antenna above a perfect ground and inversely as the square of the wave-length. Thus, if a change to a shorter wave-length is made in a given radiating system, the gain in radiated power will be very pronounced. Another advantage possessed by short waves (in this case, those of the order of a meter or less) is in the possibility of their being reflected. Since the waves used in radio communication are electro-magnetic in nature just as light waves are supposed to be, the phenomena exhibited by the one should be expected from the other. It is well known, in the case of light waves, that the dimensions of an efficient reflector must be large in comparison with the wave-length to be reflected. This same thing has been found to hold true in the case of radio waves. Thus for
very short wave-lengths, it is feasible to build reflectors and use directed telegraphy.

Besides their applicability to radio communication, ultra-short wave oscillators (capable of producing waves less than 3.0 meters in length) have been found to be very desirable tools for use on some problems in physical research. As examples, the applications made by A. Deubner (9), O. Schriefer (77), W. Mobius (56), G. Schaefer and J. Herskirk (74), and others might be mentioned.

In order to take advantage of the ultra-short waves, however, it is necessary to develop oscillators which will operate satisfactorily on them. The common forms of vacuum tube circuits, such as the Hartley, have been found to possess upper frequency limits. For commercial tubes, the shortest wave-lengths attainable lie between 1.0 and 2.8 meters. These limits are determined by two factors:

1. The inductance and capacity of the leads forming the oscillatory circuit, and the inter-electrode capacity of the tube.

2. The time of passage of an electron from the filament to the plate.

Numerous attempts to lessen the effect of the first factor have been made, and it now appears impracticable to reduce the wave-length further by diminishing the value of the circuit constants. While the influence of the second limiting item may be
controlled somewhat by increasing the anode potential, a practical limit will soon be reached.

Sustained oscillations in ordinary vacuum tube circuits are dependent on the fact that an electrical disturbance, which produces a variation in the grid potential, will be followed by a change in the plate current. This change in plate current, in turn, indirectly induces a voltage in the grid circuit which will support the initial disturbance. While it is ordinarily assumed that the plate current follows the grid voltage variations instantaneously, that is not the true case. A change in grid voltage causes the number of electrons passing through it, on their way to the plate, to vary. The maximum effect is exerted on the electrons in the filament-grid space. Thus it is seen that after passing through the grid, the number of electrons in any section of the grid-anode space will be determined by the sign and magnitude which the grid voltage possessed at the time when they were in the filament-grid region. Before the plate current can exert any influence in the grid circuit, it is necessary that those electrons reach the plate. A certain period of time must, therefore, elapse before electrons which were influenced by changes in the grid voltage can reproduce similar variations in plate current. By making an approximate calculation of the time of travel of an electron from the filament to the anode in an ordinary tube, Hollmann (32) obtained a value of \(0.7 \cdot 10^{-9}\) sec. This is of the same order of magnitude as half the period of oscillation of a 1.0 meter wave, this
latter amounting to $1.7 \times 10^{-9}$ sec. In view of this circumstance, it is apparent that too great a phase difference will occur between the potential induced by currents in the plate circuit and the grid potential variation for the latter to be sustained. It thus appears that the usual types of circuits can only be used effectively on wave-lengths above 1.0 meter.

Wave-lengths below 1.0 meter may be obtained with three-electrode vacuum tubes, in which a symmetrical potential distribution can be produced, in the manner described by H. Barkhausen and K. Kurz (1). However, the operation of the oscillator discovered by these two men is basically different from the types heretofore discussed.

Because of the fact that they are produced by a back and forth movement of electrons about the grid, Barkhausen-Kurz oscillations have only small intensities. This is probably one of the chief reasons why this form of oscillator has received little attention in the United States. It has been the subject of a large amount of experimental work, however, in both Germany and England.

Since a study of this form of oscillator would constitute a relatively new subject, the work that is reported in this thesis was undertaken. The aim pursued was two-fold:

1. To attempt to confirm or disprove the results obtained by other experimenters in this field.

2. To endeavor to obtain beats between a Barkhausen-Kurz oscillator, and one that was known to produce continuous oscillations.
II. HISTORICAL.

A. The Work of Barkhausen and Kurs.

1. Discovery of the oscillations.

H. Barkhausen and K. Kurs (1) discovered the high frequency oscillations that now bear their names while attempting to find the degree of vacuum in a three-electrode tube.

It had been known for some time that if the grid of a triode were held at a rather high positive potential while the plate was maintained at one of small negative value, the magnitude of the plate current would be an accurate measure of the gas pressure within the valve. The principle of this pressure gauge is quite simple. Electrons on leaving the hot cathode, move to the positively charged grid. In their flight, however, they produce positive ions by collisions with the gas molecules. The positively charged ions, of course, move to the negatively charged plate, and thus give rise to a plate current. This positive-ion plate current is then a measure of the gas residue in the tube.

While making such a vacuum test, Barkhausen and Kurs noticed that a current flowed in a direction opposite to that which should have been taken by one caused by positive ions. This current persisted for anode voltages as low as -100 volts. Since the only apparent reason that might have been given for this phenomenon was the existence of oscillations in the cir-
suit connected to the valve, attempts were made to discover this assumed alternating potential. The occurrence of oscillations was first established by means of a detector and galvanometer that were connected to windings placed closely about the tube. Thus the otherwise unexplainable negative, plate-circuit current was accounted for.

The frequency of the oscillator was investigated by means of Lecher wires. It was found to be scarcely influenced by the external capacity and inductance; on the other hand, it became greater for increased filament currents, increased positive grid potentials, or negatively increased plate potentials.

2. Hypothesis advanced by Barkhausen and Kurz.

From their observations, Barkhausen and Kurz concluded that the processes in the interior of the tube were responsible for the existence of oscillations. They accordingly advanced the following hypothesis to explain how oscillations were produced:

The electrons emitted by the hot cathode move with an increasing velocity to the positive grid. However, only a small number strike the thin grid wires, the greater number pass on through toward the anode. But with the anode held at a lower potential than the negative side of the filament (relative to which all potentials are referred), the electrons cannot reach it and are slowed down. When their velocity becomes equal to zero, they reverse their direction of travel
and move back toward the grid. Again, however, only a small number strike it, the greater number passing on through. Most of the electrons are thus compelled to oscillate to and fro about the grid a number of times before finally striking it. This purely mechanical backward and forward motion of electrons causes the electrical oscillations.

In order for this explanation to be true, it is only necessary that an arrangement among the electrons comes about so that a majority are found moving, somewhat as a group, in nearly the same phase.

3. Derivation of a wave-length formula.

After making some simplifying assumptions, Barkhausen and Kurr derived an expression for the wave-length. The effect of space charge was neglected, and the actual cylindrical arrangement of electrodes was considered replaced by a plane arrangement.

In the first case considered, it was assumed that the filament and plate had no potential difference existing between them. If a positive potential difference $E_g$ is applied between the grid and the cathode, the velocity of the electrons on passing through the grid will be

$$v = \sqrt{\frac{2 \times 8.6 \times E_g}{m}} = 6.0 \times 10^7 \sqrt{E_g} \text{ (cm./sec.)} \quad (1)$$

where $E_g$ is measured in volts.
Equation (1) gives the maximum velocity that is attained by the electrons; the average velocity is only one-half of this, that is

$$\bar{v} = \frac{v}{2}$$

(2)

where $\bar{v}$ signifies the average velocity.

The period of oscillation is equal to the time required by the electrons to pass from the filament, through the grid to the plate and then back to the filament. The total distance that is travelled over will be designated by $d_a$. If $T$ represents the period of oscillation in sec., and $d_a$ is measured in cm.,

$$TT = d_a = \frac{V}{2} T$$

(3)

While the electrons are making a complete oscillation about the grid, they give rise to an oscillatory current in the grid-plate circuit. This latter causes an electromagnetic disturbance that is propagated in space with the velocity of light. Since this disturbance constitutes the emitted wave, it will also have a period equal to $T$. Its wave-length $L$ may be found from the relation

$$L = cT$$

(4)

where $L$ is measured in cm., and $c$ signifies the velocity of light in cm./sec.

If equation (4) is divided by (3), the following result is obtained:
\[ \frac{L}{d_a} = \frac{2c}{v} \quad (5) \]

After substituting the right-hand member of (1) for \( v \), (5) becomes

\[ \frac{L}{d_a} = \frac{c}{3.0 \cdot 10^7 \sqrt{E_o}} \quad (6) \]

Equation (6) may be simplified by replacing \( c \) with its numerical value \( 3.0 \cdot 10^8 \) cm./sec., and multiplying both sides by \( d_a \). After this is done, the following expression is obtained for the wave-length:

\[ L = 1000 \frac{d_a}{\sqrt{E_o}} \quad (6a) \]

If the anode is at a negative potential, expression (6a) must be modified to take account of the fact that the electrons will reverse their direction of travel at the new zero potential plane. The distance from the cathode to the zero potential plane, called \( d_{1/2} \) by Barkhausen and Kurz, may be found quite easily. When it is expressed in terms of electrode distances and potential differences,

\[ d_{1/2} = \frac{d_a E_a - d_e E_e}{E_g - E_o} \quad (cm.) \quad (7) \]

where \( E_a \) is the potential difference in volts between plate and cathode and \( d_e \) is twice the perpendicular distance from the cathode to the grid measured in cm.
The final expression for the wave-length may now be obtained by substituting the right-hand member of (7) for the distance \( d_a \) in (6a), that is

\[
L = \frac{1000 \cdot d_a E_a - d_h E_a}{\sqrt{E_h - E_a}} \quad \text{(cm.)}
\]  

(8)

By substituting plate and grid diameters for \( d_a \) and \( d_g \) respectively in equation (8), Barkhausen and Kurs were able to make a rough comparison between measured and calculated wave-lengths for the same potentials. In all cases, the calculated values were found to be greater than those observed. These deviations were partly explained by the action of space charges in reducing the distance of travel of the oscillating electrons.

4. Results of other experiments.

Tests were made on tubes having various electrode forms in an attempt to determine their effect. It was found that all models, except those having symmetrically arranged cylindrical elements, were incapable of producing the high frequency oscillations described. From this it was concluded that an electric field having a regular shape was required for exciting electron oscillations.

Valves whose grids were made up of few turns of thick wire were also found incapable of acting as oscillators even when a cylindrical electrode arrangement occurred. The reasons given for this were the absorption of too many electrons by the large wires, and the fact that the cylindrical symmetry was greatly
distorted due to the influence of the individual wires on the electric field.

Experiments showing the directional effect of an antenna were also made. For this purpose two straight pieces of wire were connected to the grid and plate electrodes of the transmitter. A receiver consisting of a crystal detector and a sensitive galvanometer was provided with similar wires. With this receiving set-up, it was found possible to establish quite accurately the direction of an invisible transmitter. The greatest galvanometer deflection was obtained only when the receiving and the transmitting antennas were parallel to each other.

B. Barkhausen and Kerz Oscillations.

If Barkhausen and Kerz had not discovered the oscillations that now bear their names and published the results of their investigation of them in 1920, credit for this would have gone to S. J. Zilitinkewitsch (30). Without any knowledge of the work of Barkhausen and Kerz, he discovered these oscillations in 1921.

The work of Zilitinkewitsch was done in Russia during the Winter of 1921 and the Spring of 1922. The results of his investigation were presented before the Russian Physical Congress in September, 1922, and published a short time later. At that time almost all Russian works were carried out independently of
similar efforts in foreign countries, because of Russia's complete isolation.

An interesting fact is that Zil'itinskiiwitch, in agreement with Barkhausen and Kurz, gave the oscillatory motion of electrons about the grid as the cause of the oscillations.

From rather involved theoretical considerations, he derived the following expression for the wave-length:

$$ L = \frac{1000}{\sqrt{E_0}} \sqrt{\frac{\delta_f}{\delta_p}} \left( 1 - \frac{e_1}{e_2} \right) $$

In this equation, \( \delta_f \) represents the distance between filament and grid surfaces, and \( \delta_p \) the distance between the grid and plate; \( e_1 \) and \( e_2 \) are constants depending on the parameters of the tube, emission current, and applied potentials.

A rather good agreement was found to exist between his observed wave-lengths and those calculated from his formula.

In an interesting experimental study of the field strength about a Barkhausen-Kurz oscillator, L. Bergmann (3) confirmed predictions that had previously been made from theoretical considerations.

Since Barkhausen and Kurz had stated that the external circuit did not affect the wave-length of the oscillations discovered by them, E. W. B. Gill and J. H. Morrell (22) assumed that Lecher wires could be connected directly to the grid and plate electrodes for making wave-length measurements. A bridge consisting of two fixed condensers between which the heater element of a thermo-couple was connected, was arranged to slide
along the Lacher wires.

From facts known at that time, it was expected that the 
distances between successive bridge positions, at which maxi-
num current values were detected, should be equal to one-half 
the wave-length of the generated oscillations. This was not 
found to be the case. At times equally-spaced positions were 
found, but in the majority of cases there were at least two 
sets of positions forming two series of equal spaces. Since 
the spacing of the two sets was different, it appeared that two 
optimum wave-lengths were being produced.

Gill and Morrell regarded these effects as due to the dif-
ferent modes of oscillation of the system. They then advanced 
a theory, based upon the work done by electrons, which qualita-
tively accounted for the maintenance of the observed oscilla-
tions.

The four chief assumptions made in connection with their 
theory are:

1. That the grid and plate can be regarded as forming 
a parallel plate condenser,

2. That of the electrons which leave the filament, a 
fixed small proportion pass through the grid in a uniform 
stream, and that each electron on passing through the 
grid has the same velocity.

3. That the electrons which return to the grid from 
the plate side are nearly all collected directly on it, 
i.e., only a few pass through on the return journey.
4. That the oscillating potential differences are small compared with the fixed potential differences employed.

From their observations, Gill and Morrell concluded that wires or conductors connected to the electrodes were a necessary part of the oscillatory system.

Subsequent investigators have shown that the oscillations observed by Gill and Morrell are distinctly different from those found by Barkhausen and Kurz, though they may both be produced in the same circuit.

The theoretical and experimental treatment of Barkhausen-Kurz oscillations by A. Scheibe (76) has probably been the most important contribution relating to them since their discovery was first announced.

In his experimental investigation, Scheibe's aim was to find how the wave-length varied with the electrode dimensions and the applied potentials, and to determine the constancy and the intensity of oscillations. His theoretical work was concerned with deriving an expression for the wave-length produced by tubes having elements that were concentric cylinders.

Experiments carried out since the results of Scheibe's work were published indicate that his wave-length formula is not generally applicable. However, it has assumed a significant rôle as a basis upon which comparisons can be made. The wave-length expression, in condensed form, is
\[ L = \frac{4\sigma r_1}{\sqrt{2\frac{E_g}{m}} 10^8} \left\{ f \left[ \sqrt{\log \frac{p_1}{p_0}} \right] + g \left[ \sqrt{\frac{E_g - E_a}{E_g - E_a} \log \frac{r_a}{r_1}} \right] \right\} \]

where

- \( L \) = Wave-length (cm.).
- \( c \) = Velocity of light (cm./sec.).
- \( e \) = Electronic charge (e.m. unites).
- \( m \) = Mass of electron (gm.).
- \( E_g \) = Potential of grid electrode (Volts).
- \( E_a \) = Potential of plate electrode (Volts).
- \( r_c \) = Radius of filament wire (cm.).
- \( r_1 \) = Radius of grid electrode (cm.).
- \( r_a \) = Radius of plate electrode (cm.).

The functions

\[ f \left[ \sqrt{\log \frac{p_1}{p_0}} \right] \]

and

\[ g \left[ \sqrt{\frac{E_g - E_a}{E_g - E_a} \log \frac{r_a}{r_1}} \right] \]

have the forms

\[ f(x) = xe^{-x^n} \int_0^x s^a du \]

\[ g(x) = xe^{-x^a} \int_0^x e^{-u^a} du \]
Curves representing these last expressions are shown in figures 1 and 2.

In deriving this formula, Schaebe made a number of simplifying assumptions, five of which were as follows:

1. The grid acts as a cylinder rather than as a cylindrical helix.
2. The potential distribution is not modified by moving electrons.
3. The amplitude of the oscillations is negligible in comparison with the potential applied to the grid.
4. The initial velocity of electrons on leaving the filament is zero.
5. No space charge regions exist.

Deviations of calculated wave-lengths from observed values have frequently been attributed to the fact that some of these assumptions are not justified in practice.

While carrying out the experimental work, a new range of oscillations was discovered in which the wave-length was about one-half of that of the corresponding Barkhausen-Kurz oscillations. It was found that the length of these short waves was dependent upon the applied voltages and currents. Their behavior was similar to that of the long waves in so far as constancy, reproduciveness, and being unaffected by the connected circuit were concerned.

The results of the study of Barkhausen-Kurz oscillations indicated that the wave-length is practically dependent on only
\[ f(x) = xe^{-x} \int_{0}^{x} e^{u} du \]
$$g(x) = xe^{x^2/2} \int_0^x e^{-u^2} du$$
the applied voltages and tube dimensions; it is either independent of the outer oscillatory circuit and filament current or it is only influenced by them to a small extent. When Scheibe compared the wave-lengths observed for definite grid and plate potentials with the corresponding values that were calculated from his formula, he found them to be in very good agreement.

Tests repeated after several minutes had elapsed showed that the wave-length remained very nearly constant.

The intensity of the oscillations was found to be greatly influenced by the oscillatory circuit. Curves plotted between oscillation intensity and wave-length generally indicated the occurrence of rather sharp maxima. In a later article, Scheibe (76) explained how short Lecher wires, connected to anode and grid electrodes, could be instrumental in reinforcing the oscillation intensity.

A rather extensive study of Barkhausen-Kurz oscillators that were built up of two or more tubes operating in parallel was made by M. T. Grechova (25). Wave-length measurements were carried out with a two-tube generator in which the plate potentials were varied from -6.0 to +14.0 volts and the grid potentials from +50.0 to +160.0 volts. It was found that for this set-up, the wave-length was also dependent upon the filament current, grid and plate potentials, and the ratios of the anode to the grid diameters. However, the wave-lengths calculated from Scheibe's formula and that of Barkhausen and Kurz did not
agree with the observed results for corresponding potentials. It was also found that the oscillations were affected by changing the dimensions of the leads in the plate circuit. A simplified diagram of the two-tube circuit used is shown in figure 3.

Experiments with a circuit in which the number of tubes was varied from one to seven showed that the intensity of oscillations increased rapidly with the number of tubes.

An investigation to determine the effect of residual gas pressures was also made by Grechowa. It was found that both the wave-length and oscillation intensity were affected by pressures in a range extending from $5.0 \times 10^{-5}$ mm. Hg, to $1.0 \times 10^{-4}$ mm. Hg. At a pressure of about $1.0 \times 10^{-5}$ mm. Hg., the oscillations disappeared.

By taking into consideration the form of the grid-plate current—grid-plate voltage characteristic of a triode whose grid was held at a high positive potential relative to the filament and plate, J. Sahanske (71) was able to advance a theory that explained the oscillations produced by such a set-up.

From this theory a number of interesting conclusions were drawn. One that is of practical interest and which has been confirmed experimentally is as follows:

"Tubes having cylindrical electrodes can be used in the production of oscillations in the assumed circuit so long as the ratio of the anode radius to that of the grid is restricted to the limits

$$2.0 < \frac{r_a}{r_g} < 5.0$$
Two-Tube Oscillator Circuit Used By M.T. Grechowa

Figure 3.
\[ r_g = \text{radius of the plate.} \]
\[ r_g = \text{radius of the grid.} \]

Sahnow also concluded that it would be possible for a tube, whose grid was eccentric to the anode, to act as an oscillator provided that the eccentricity did not rise above a certain limit.

At about the same time that Grechowa was carrying out an investigation to determine the effect of residual gas pressures on certain characteristics of a Barkhausen-Kurz oscillator, N. Kapzov (43) was making a similar study with tubes containing mercury vapor.

Kapzov's results indicated that the wave-length of the oscillations was dependent on the mercury vapor pressure, and this dependence was especially marked at low grid potentials. Tests made on tubes having cylindrical electrodes and possessing low mercury vapor pressures showed that oscillations could be produced with small filament currents and very low grid potentials.

In an experimental way, N. Kapzov and S. Groesdower (44) established conditions under which electron tubes having cylindrically arranged electrodes can generate, in one case, the type of oscillations observed by Barkhausen and Kurz, while in another instance, those noted by Gill and Morrell. It was also shown that both forms of oscillations could be produced by one and the same tube.
W. Wechsung (32) found that short wave oscillations could still be obtained when rather high alternating potentials were applied to the grid of a tube that was connected in a Barkhausen-Kurz circuit. His results showed that the wave-length decreased almost linearly with increasing grid potentials. A comparison between the observed wave-lengths and those calculated from Scheibe's formula, when the peak values of the grid potentials were used in it, revealed that the former were all much shorter than the latter.

A rather interesting phenomenon that was observed when wave-length measurements were being made on Lecher wires was the tendency of the current maxima to broaden for increased frequencies of the alternating grid potentials.

In a mathematical treatment, O. Pfetscher (61) developed a theory that explained how the so-called "Gill-Morrell" oscillations were produced. It was based upon a solution of the differential equation of motion of electrons in the grid-anode space, and was able to explain how the electrons became separated into the group collected by the anode and that gathered by the grid. The necessity for such a separation had already been pointed out by Gill and Morrell when they first sought to find the mechanism of these oscillations.

In view of the fact that proof of the existence of the electron motion required by the simple Barkhausen-Kurz theory had never been given, K. Kohl (47) offered a new theory that was based upon a variable grid-plate capacity. The electrons
in the grid-plate space were regarded as an "electron gas" whose dielectric constant was less than unity. A. Einstein had shown that the dielectric constant of such an "electron gas" was given by the expression

\[ \kappa = 1 - (\text{constant}) \cdot \pi^2 \]

where \( \pi \) signifies the electron density, and \( L \) the wavelength of the oscillations.

Kohl assumed that the frequency of the oscillations is determined by the constants of the oscillatory circuit. The variations observed, when grid and plate potentials were changed, or the emission current varied, were explained by the changes in electron density.

The shortest waves which Scheibe had observed while studying the regular Barkhausen-Kurz oscillations, were made the subject of a rather extensive investigation by O. Potapenko (66). He called the oscillations appearing in this short-wave group "dwarf waves", in order to distinguish them from the longer, normal waves.

Scheibe and other experimenters had observed a class of these dwarf waves whose frequency was about twice that of the oscillations expected from the Barkhausen-Kurz theory. According to Potapenko's terminology, these were of the first order. In the course of his own study, however, he succeeded in securing data on as high as the fourth order waves.

The results obtained indicated that dwarf waves are oscil-
lations of the circuits within the tube or coupled with the tube which are excited in such a manner that during the time $T$ it takes the electrons to pass from the filament to the plate and back, the circuits perform two complete oscillations (dwarf waves of the 1st order), three complete oscillations (dwarf waves of the 2nd order), etc. Thus the wave-lengths of the normal and dwarf waves are represented by the following relationships:

\[ L_n = cT \quad \text{(Normal waves)} \]

\[ L_1 = c \frac{T}{2} \quad \text{(Dwarf waves of the 1st order)} \]

\[ L_2 = c \frac{T}{3} \quad \text{(Dwarf waves of the 2nd order)} \]

\[ L_3 = c \frac{T}{4} \quad \text{(Dwarf waves of the 3rd order)} \] etc.

where $c$ is the velocity of light.

Potapenko stated that while the wave-lengths of dwarf waves may coincide with those of the overtones of the grid and the plate circuits, they cannot be considered as such. Dwarf waves differ from overtones in that they are completely independent of normal waves. They were observed, in fact, for some grid potentials at which normal waves could not be produced.

A very important conclusion to be drawn from these data is that a vacuum tube can generate oscillations whose frequency exceeds many times the frequency of electronic oscillations.

A study of the manner in which grid current, plate current, and oscillatory current varied with grid voltage, in a Bark-
hanssen-Kure circuit, was made by W. J. Kalinin (41). He found that as the grid potential was increased, the plate potential being held equal to zero, rather sharply defined maxima of plate current and oscillatory current occurred. These only appeared in certain, narrow voltage ranges. The grid current increased quite rapidly as the grid potential moved from its zero value, but the rise became more gradual at the higher potentials. In those voltage ranges where these plate current and oscillatory current maxima occurred, abrupt drops in the grid current curve appeared.

It was shown that the centers of these so-called oscillatory regions, that is, the voltage points corresponding to maximum values of plate current and oscillatory current, were distributed along the abscissa according to the law

\[
\frac{V_{n+1}}{V_n} = \frac{V_n}{V_{n-1}}
\]

where \(V_{n+1}\) is the grid voltage at the center of the \(n+1\) range, \(V_n\) in that of the \(n\) range, and \(V_{n-1}\) in that of the \(n-1\) range.

An important series of investigations of both the Barkhausen-Kure oscillations and those discovered by Gill and Morrill was made by H. E. Hellmann (34). He found, as had also Kaprov and Grostower, that both types could be produced by one and the same tube. The apparatus which he used in demonstrating this was similar to that first employed by Gill and Morrill.
One set of Lecher wires was joined to the grid and plate electrodes. Along these traveled a bridge made up of a thermocouple connected in series with and in between two condensers. A second system was used for making wave-length measurements. By plotting a curve between observed wave-lengths as ordinates, and the distances of the bridge from the center of the oscillator tube as abscissae, Hollmann showed that two distinct regions of oscillations existed. In one of these, the wave-length was practically independent of the length of the Lecher wires in circuit (Barkhausen-Kurz oscillations), while in the other, it was dependent on this length (Gill-Morrell oscillations). By considering the effect of the changing amplitude of the alternating potential between grid and plate as the external oscillatory circuit was being varied, Hollmann was able to explain the transition from one form of oscillation to the other.

A theory that explained how the electron arrangement required by the Barkhausen-Kurz theory might come about was advanced by H. C. Müller (57). He based this on what he called "Excitation according to the sorting-out principle."

It is known that the distance, in the grid-plate space, over which electrons will travel depends upon the potential difference through which they have fallen (grid-filament voltage), and upon that existing between the grid and the plate. If an alternating potential difference is added to that already in the grid-plate circuit, this distance will fluctuate. Assuming that the filament and anode were originally at the same po-
tential, the electrons would have reversed their direction of travel at the plate. The addition of the alternating potential causes some of them to reverse their flight before the anode while others are actually collected on it. Those reversing their direction of travel move back toward the grid. It is thus seen that the alternating potential causes a "sorting out" of electrons. Those moving back to the grid later form the oscillating charge. A part of this oscillating charge is collect- ed by the grid on each passage through it and, if the phase re- lations are correct, sustains the oscillations.

In addition to this explanation, Müller indicated there might be a second method of attaining the same result. This he called "Oscillations that are excited according to the principle of fluctuations in the time of transit of electrons between electrodes." However, no evidence was offered to establish the correctness of this latter theory.

A study of the influence of various gas pressures on Bark- hausen-Kurz oscillations was recently made by K. Hindfleisch (67). His aim was to determine whether gases were necessary for the excitation of oscillations, and what effects were produced on the oscillatory ranges, wave-lengths, and oscillation intensities.

The results of the investigation indicated that maximum power was developed in high vacua although pressures up to about $6.0\cdot10^{-5}$ mm. Hg caused no essential diminution. In all cases, gas-filled tubes caused a variation in oscillation in-
tensity and a lengthening of the wave. With increasing pressure it was found that the starting point of oscillations moved towards lower grid potentials. However, pressures above $5.0 \times 10^{-8}$ mm. Hg caused no further changes in this respect.

Rindfleisch concluded that the presence of gas was not necessary for the excitation of oscillations.
C. Continuous Wave Oscillators.

One of the first to investigate the upper frequency limit of three-electrode vacuum tube oscillators was W. C. White (84). In 1916, he sought to determine to how high and to how low a frequency a new type of pliotron would oscillate. The particular valve used by him developed ten watts of energy while operating on a wave-length of 6.0 meters.

The circuit used by White is shown in figure 4. The oscillating inductance in the plate circuit consisted solely of the connecting wire bed, between filament and plate, and in the grid circuit of efga. Each of these wires was only a few inches long. The oscillator is shown connected to Lecher wires through the small condensers $C_g$ and $C_s$. By sliding the bridge $W$ along the wires $J$, the wave-length could be determined.

By using the circuit shown in figure 5, which is essentially the same as that used by White, Sutton and Toulouse (29) succeeded in obtaining waves having lengths of less than 2.0 meters. In their case, however, it was found advantageous to use a grid condenser $D$ possessing a capacity of $10^{-6}$ microfarad and a grid resistance $R$ of 10,000 ohms.

The complete oscillatory circuit consisted of the wire loop abcd, in which is inserted a blocking condenser $C$, and the inter-electrode capacity of the tube. The capacity of $C$ ranged from $10^{-3}$ to $2 \cdot 10^{-5}$ microfarad. In constructing an oscillator of this type, it was found desirable to fix the
Oscillator Circuit Used By W. C. White

Figure 4.
Figure 5.

Oscillator Circuit Used by Gutton and Toully
length of the wire ad and determine the most favorable length of wire ab by trial.

The effective intensity of the oscillatory current was indicated by the hot-wire type ammeter A. In order to prevent this high frequency current from entering the battery circuit, two choke coils, \( S_1 \) and \( S_2 \), were connected on each side of the blocking condenser.

A parallel wire system \( L \) was used in determining the wave-length.

B. van der Pol (34) found that by using an ordinary receiving tube in White's circuit, a wave-length of 3.35 meters could be reached. He then made a study of the type of maxima that this oscillator produced in a Lecher wire system.

In 1919, W. H. Eagles and F. W. Jordan (14) presented several papers that dealt with two-tube circuits. These were later to become very popular for operations on the short wave-lengths.

A two-tube oscillator circuit that was developed a few years later by F. Holborn (37) is shown in figure 6. The wave-length of this type of oscillator is varied by changing the effective length of the grid and anode leads. These are seen to consist partly of branches that are made up of parallel conductors. As parallel leads, Holborn used brass tubes which were separated a distance of 5.0 cm.

Wave-lengths of 2.4 meters were reached with this circuit. It was found, however, that the power developed fell off rapid-
Oscillator Circuit Used by F. Holborn

Figure 6.
ly for waves below 3.4 meters.

In an attempt to reduce the inter-electrode capacity and the length of connecting leads to a minimum while still realizing the advantages of a two-tube oscillator, A. Danilewsky (8) constructed a special five-element valve for producing short wave oscillations.

This tube consisted of two plates and two grids placed on opposite sides of a common filament. The anode plates were fastened to a small glass frame at their top and bottom ends and the grid wires were wound on the sides of this support. Thus each grid surrounded its plate. The grid-anode distances as well as the filament-grid distances amounted to about 2.0 mm. The filament was also supported by a small frame.

By using this tube in the circuit shown in figure 7, oscillations having wave-lengths of 2.0 meters were produced. The inductances were made up of rectangular loops of wire. When used on the shortest wave-lengths, these loops had dimensions of 8.5 cm. and 2.0 cm. That is, \( L = 8.5 \text{ cm.} \) and \( D = 2.0 \text{ cm.} \)

Research work on short wave telegraphy had been undertaken at the French Military Radio-Telegraphic Laboratory in 1914, and at that time Sutton succeeded in producing waves having lengths of the order of a meter. However, the technique of reception was not then sufficiently advanced to permit satisfactory communication. Under the stress of war conditions, this research had to be abandoned. It was resumed some time later, and M. Nesney (55) reported the results that were obtained.
Oscillator Circuit Used By A. Danilewsky

Figure 7.
The oscillator was of the two-tube type having the circuit shown in figure 8. Single spirals that were 9.0 cm. in diameter served as inductances.

Wave-lengths as low as 1.2 meters were reached with this set-up. The operation was found to be very stable on 1.5 meters, and the radiated power corresponding to this wave-length was about 30 watts.

The aim of an experimental investigation carried out by C. Gutton and E. Pierrat (29) was to determine the possibilities of isolating and amplifying harmonics produced by short wave oscillators. In the account of their work, they described the circuits used, the methods employed in creating dissymmetry in them, and the number of harmonics obtained.

By employing the circuit used by Gutton and Touly and applying a potential of +45 volts to the grid of the oscillator valve, the second, third, and fourth harmonics were produced. The fourth harmonic which was particularly intense corresponded to a wave-length of 54.0 cm. It was also found possible to cause dissymmetry in this circuit by changing the length of the wire connecting the plate to the blocking condenser (ab in figure 5), and by coupling the grid and plate leads inductively.

Harmonics up to the seventh were detected in oscillator circuits employing two tubes operating in parallel. In the series circuit used by Mesny, only the second, third, and fourth harmonics were found. Of these, the third was the most
Oscillator Circuit Used By M. Mesny

Figure 8.
For the purpose of studying electric waves on wires, W. S. Huxford (40) employed an oscillator having the circuit shown in figure 9. This is somewhat similar to those used by White, Sutton and Touly, and van der Pol. An important difference, however, is that Huxford followed suggestions that were first made by G. C. Southworth (79), and used parallel leads in his oscillatory circuit rather than curved loops. This practice of employing "distributed" rather than "lumped constants" has been followed in more recent years.

The valve used was a modified form of Radiotron UW202 in which the grid connection had been fused through the top of the glass tube. The electrostatic coupling between grid, plate, and filament was thus reduced. The oscillatory circuit outside the triode consisted of two horizontal brass tubes, 5.0 mm. in diameter, that were soldered to the plate and grid leads and into which two brass rods were fitted to form a telescoping system; a condenser C was connected across the rods. This latter was adjustable as to spacing of plates, and as to position along the brass leads.

The range of wave-lengths obtained with this set when employing rods and tubes 20.0 cm. in length was from 1.0 to 3.0 meters.

It has been known for some time that sustained oscillations may be produced by placing a suitable "negative resistance" in shunt with a condenser and connecting the combination
Oscillator Circuit Used by W. S. Huxford

Figure 9.
in series with an inductance and resistance of certain values. The application of this principle to vacuum tube oscillators was made by F. Kiebits (46).

By plotting a curve that was derived from the Plate Current-Grid Potential characteristic, and which had plate current as ordinates and potential difference between plate and grid as abscissae, he found that the property of "negative resistance" should be exhibited by tubes in a certain range. He found that by connecting oscillatory circuits between the grid and plate of a valve, it actually would display this falling characteristic. In this way, oscillations having periods ranging from 5 sec. to 10−6 sec. were generated. The circuits used were somewhat similar to that employed by Huxford.

In one of the 1927 issues of "Radiotechnik", P. Hollmann described a triode transmitter with which he produced oscillations having a wave-length of 92.0 cm. The diagram of connections of this oscillator is given in Figure 10, and it may be seen there that the chief difference between Hollmann's set-up and Huxford's is in the disposition of the condenser in the external circuit. The former connected his directly at the grid while in the case of the latter it served as a movable bridge on the plate and grid leads.

A brief comparison of the characteristics of this type of oscillator with those of a Holborn set was made by A. Deubner (9).

Cited in a paper by A. Deubner (9). Original article not examined.
An investigation of the practical short wave limit of vacuum tube oscillators was made by C. R. Englund (16). In his experiments, it was found that shorter waves could be obtained by means of a double tube asymmetrical oscillator than could be gotten by a single tube arrangement. This was due to the fact that the total length of conductors carrying oscillating currents could be reduced, in the double tube connection, below what could be reached by means of a single tube. The joining of a “Lecher Wire” system to the vacuum tube did not appear to be any more conducive to the reaching of shorter wave lengths than did the ordinary use of “lumped constants”. Attempts were also made to lower the wave-length by increasing the plate voltage and filament current. It was found that a plate voltage increase alone was of no use if the filament did not have a corresponding emission of electrons. In fact, the tests indicated that a very active filament was the backbone of a short wave oscillator.

A special valve was built which really incorporated into one tube the elements of two. Small loops were connected to the electrodes through the glass walls of the bulb. With this arrangement a wave-length of 1.05 meters was reached. The oscillations at this point, however, were rather unstable.

A circuit that is identical with Nessy’s was employed on the ultra-short wave-lengths.

L. Bergmann (4) found that the tube capacity could be greatly diminished by leading the grid and anode wires out on
opposite sides of the glass bulb, rather than through the base as is generally the practice. By using an ordinary tube of French manufacture, in which the leads were brought out this way, he succeeded in reaching a wave-length of 82.0 cm. The first circuit used was similar to that devised by Hollmann, but it was found by experience that slightly better results could be obtained with one that was identical with Huxford's. In the ultra-short wave region, it was found that the wave-length varied directly as the length of the lead connecting the plate and condenser bridge.

Some time later, Bergmann (2) investigated the effect of choke coils in the filament leads and found that the signal strength of an oscillator depended in a large measure on a proper choice of their values. It appeared that for each wave-length, a particular size was necessary. Since a constant changing of choke coils for each variation in frequency would be impractical, he avoided such a procedure by shunting variable condensers around the chokes. This arrangement proved extremely satisfactory, as it was only necessary to adjust the condensers for each change in wave-length.

Short wave experiments, in which an alternating potential was applied to the plate, were made by H. Wechsung (33). By using a slightly modified Telefunken Type RS19 tube and applying 5000 volts to the anode, he succeeded in obtaining a power radiation of 150 watts on a wave-length of 3.0 meters. The circuit employed was similar to that of Sutton and Touly.
R. L. Smith-Rose and J. S. McPetric (79) showed the evolution of several single-valve and two-valve circuits and gave brief analyses of those most commonly used. The advantages, disadvantages, and characteristics of oscillators using them were pointed out. In a later article, photographs of transmitters that employed the circuits developed in their first paper were shown. The design data applying to these set-ups were also given.

Experiments whose object was to determine whether ultra-short waves could be used with any reasonable amount of success for communication at ground levels were made by C. C. Whitehead (85). In regard to propagation, he found that in many respects their behavior was similar to that of light waves. They could, therefore, be used with maximum efficiency only under conditions somewhat like those required for light waves. A very interesting phenomenon, noticed by Whitehead while receiving, was the total absence of any noise due to atmospherics. He found this to be true in all kinds of weather, including thunderstorms.

A review of the types of vacuum tubes adapted to operation on short waves was made by E. D. McArthur and E. E. Spitzer (53).
In 1900, E. Lecher (52) presented a paper which dealt with the resonance phenomena occurring in two parallel wires. The work upon which this was based later became the forerunner of a series of valuable experiments. These latter ultimately ended in the development of a wave-meter for use on the short electromagnetic waves employed in radio communication.

His experimental set-up consisted of two parallel wires having a diameter of about 1.0 mm., and a variable separation of from 10.0 to 50.0 cm.; the length of the wires was changed, but it was never made less than 400.0 cm. Across one end of the wire system he placed a glass tube which had first been evacuated, and then refilled with nitrogen and a trace of turpentine vapor. A second bridge, made of metal strap, was also placed across the wires. This latter could be moved from one end of the system to the other.

The two remaining free ends of the parallel wire system were connected to condensers and these in turn to a Hartzian oscillator. This system of coupling is shown in figure 4.

When the wires were excited, the glass tube was found to glow for certain, sharply-defined positions of the metallic bridge. Analysis of this phenomenon indicated that the distance between any two consecutive places, at which resonant states occurred, was equal to one-half the wave-length of the exciting disturbance.

Several years after Lecher's work had been published,
F. Drude (10) gave a mathematical treatment of the subject. In
the first part of his paper, Drude dealt with wires which were
completely surrounded by air. The second part was concerned
with the case of parallel wires having a portion of their length
embedded in a conducting medium (for example, a salt solution),
while the remaining portion was in air. This article has be-
come recognized as the most complete treatment on the subject
of standing waves on wires.

A short time after Drude's results had been published,
W. D. Morton (59) made a study of the effects of a "lumped"
capacity on the stationary electrical waves. He found that the
nodes on the two sides of a condenser that had been placed
across the wire system tended to move together. The amount of
this movement depended on the position of the inserted capacity;
it was zero when the condenser was at a node, and became a max-
imum when it was midway between two nodes.

When a shifting in positions of the maxima will aid in
making measurements, this effect is sometimes used.

Since Lecher wires of reasonable length could only be used
for short wave measurements, Townsend and Morrell (81) attempt-
ed to devise a somewhat similar wavemeter for use on the longer
waves. Their apparatus consisted of a long solenoid that was
open at both ends, and a detector. The solenoid was excited by
an oscillator whose coupling coil was in a plane at right
angles to the solenoid's axis and at its center. The detector
was made up of two coils wound in the shape of a figure 8, and
connected to a lamp. One of the detector coils was made to slide along the outside of the solenoid. The figure 8 arrangement of coils made it impossible for the oscillator to light the lamp since any flux inducing a voltage in one coil would have induced a voltage of the same magnitude but oppositely directed in the other. Thus the lamp could only be lighted when the detector coil was at a point of maximum current in the solenoid.

The wave-lengths determined by this scheme were in quite good agreement with those found by other methods.

In 1933, Dunmore and Engel (12) explained a method for fixing the wave-length of oscillators operating on relatively low frequencies. This was based on the setting-up of beats between an ultra-short wave oscillator and the harmonics of the long wave set. The short wave unit served only as a standard, its wave length being determined by means of Lecher wires.

A rather complete treatment of electrical waves on wires is given in a Bureau of Standards paper that was written by A. Hund (39). The main part gives the practical deductions which are drawn from the mathematical theory, and also a method for calculating the correction to be used in obtaining the frequency. The Appendix gives the mathematical theory.

In Mr. Hund's work, the voltage and current at any point are expressed as complex functions of the voltage and current at some chosen origin, and of the line constants.

By exciting two parallel wires whose length was fixed, W. S. Huxford (40) found that his movable bridge detector lo-
cated two groups of resonance points. A short study revealed 
the fact that for each change in frequency of the exciting 
oscillations, one set of maxima would shift in one direction 
while the other set would move the opposite way. The distance 
between alternate current peaks was found to be very nearly 
the same. In all cases, this was identical for both groups of 
maxima. This, of course, was equal to half the wave-length.

Whenever the bridge was at a resonance point, Huxford con-
cluded that one section of the parallel wires, including the 
bridge, would vibrate in one of its free modes of oscillation. 
At the next resonance point, the other section would respond. 
It is thus apparent that the wave-length could be determined 
from either set of maxima.

Since the Lecher wire system that was used in the inves-
tigation described in this thesis was similar to that used by 
Huxford, it was natural that the phenomena observed by him 
should also be encountered. This was found to be the case, and 
his results were confirmed in every respect.

A curve showing the current distribution on the Lecher 
wires is shown in figure 211. The two classes of maxima are desig-
nated with the letters A and B. The data for this curve were 
obtained with a Barkhausen-Kurs oscillator exciting the wires.
III. EXPERIMENTAL.

A. Apparatus.

1. Barkhausen-Kurz oscillator.

The Barkhausen-Kurz oscillator consisted essentially of a three-electrode vacuum tube of special construction, a small oscillatory circuit and suitable voltage sources.

The triode was especially designed for this investigation. It was made up of concentrically arranged cylindrical electrodes whose diameters had been determined from the tube and wavelength data given in the reports of Scheibe (76), and Barkhausen and Kurz (1). The wave-length range in which operation was to take place was known to lie between 1.0 and 3.0 meters. Earlier investigators had found that this range embraced the lower operating limit of a normal continuous wave oscillator which was to be used, in conjunction with the Barkhausen-Kurz set, for producing beats.

The complete design data on the tube are as follows:

- Diameter of plate cylinder: 3.0 cm.
- Diameter of grid spiral: 1.2325 cm.
- Diameter of filament: 0.0203 cm.
- Diameter of wire used in the grid spiral: 0.0127 cm.
- Diameter of wire used in the grid frame: 0.0312 cm.
- Length of plate cylinder: 5.5 cm.
- Length of grid spiral: 4.5 cm.
- Length of filament: 5.0 cm.
- Turns of wire on grid spiral per cm. of length: 2.45

The grid spiral was constructed of molybdenum wire, and was
wound on a frame (two supports and two end rings) made of nickel wire.  

The filament was of pure tungsten.  
The plate cylinder was made of sheet nickel.  

A glass rod that was bent into the form of a rectangle completely supported the grid and plate electrodes, and one end of the filament. This was somewhat similar to the arrangement used by Hollmann (34). A small tungsten wire bent into a coiled spring and fixed between the glass frame and one end of the filament kept the latter taut at all times. The leads from plate and filament were led out one end of the tube while the grid lead was taken from the other.  

The oscillatory circuit consisted of the internal capacity between grid and plate electrodes and the inductance and capacity of the leads connected to them. The effective length of the wire attached to each of these was about 76.5 cm. This was measured from the plate (or grid) extreme inside the tube to the end on the outside. Since the leads were brought out on opposite ends of the tube, it was necessary to bend them around if they were to be made to run parallel to each other for any distance. This was done, and the oscillatory circuit then assumed the form of an extended letter C. Copper wire of No.8 B. and S. gauge size was used in this circuit. The distance that the plate and grid wires ran parallel to each other was about 23.0 cm. Two small insulating blocks kept this portion of their lengths separated by a distance of 2.35 cm. (measured
between wire centers).

A complete view of the oscillator tube, and the lead proceeding from the grid and plate electrodes is shown in figure 12. In this picture, the grid lead is the one seen on the right-hand side while that of the plate is seen on the left.

Storage batteries were used in lighting the filament, and in supplying the plate with the desired potential. A direct-current generator provided the potentials for the grid. Two rheostats, operated in parallel, were used in controlling the filament current. The plate potential was varied by means of a high resistance potentiometer connected across the anode battery. These two controls may be seen in figure 18a. The variable resistance on the top side of the board constitutes one of the filament rheostats while that on the bottom side is the plate potentiometer. Satisfactory control of the grid potential was obtained by varying the field current of the generator.

The oscillator circuit employed is shown in figure 13.

2. Continuous wave oscillator.

The continuous wave oscillator that was used in this investigation was patterned after one described by A. Deubner (9). It was made up of a single UX201-A amplifier valve, a small external circuit containing inductance and capacity, this being connected between the grid and the plate; and suitable batteries for lighting the filament and providing the plate potential.

In order to reduce the grid-plate capacity of the tube,
the base was removed. Further modifications in this respect, however, were found to be unnecessary as the valve then produced stable oscillations on a wave-length of about 2.5 meters.

The external portion of the oscillatory circuit consisted of two parallel copper tubes each having a length of 18.6 cm., and a 13-plate variable blocking condenser. The tubes had an outside diameter of 0.6 cm., and were separated by a distance of 2.3 cm. (measured between tube centers). A movable copper bridge was fitted on these for the purpose of changing their effective length. The blocking condenser was mounted quite close to the valve, and had its movable plates connected to the grid; the stationary set being joined to one of the copper tubes. The free end of the remaining tube was soldered directly to the plate lead.

Storage batteries were used for the lighting of the filament, and for providing the plate with the necessary potential. This latter varied from 130 to 150 volts.

A rear view of the oscillator is shown in figure 14, and the wiring diagram of it appears in figure 10.

It was found that this oscillator could be converted into a receiving set of the type described by C. Cords (7) by simply connecting a pair of receivers between the negative ends of the plate and filament batteries. Receivers are not shown in the lead joining these ends in figure 10. With this arrangement, satisfactory reception was realized on wave-lengths between 2.6 and 3.0 meters.
3. Lecher wires and detecting apparatus.

The Lecher wires that were used in making all wave-length measurements consisted of two parallel copper wires that were separated from each other by a distance of 10.0 cm. (between conductor centers), and which had individual lengths of 320 cm. The wire size employed was No. 8 B. and S. gauge. In order to insure their complete isolation, porcelain insulators were used at each end of the individual wires.

The movable bridge that was fitted on these was made of rather heavy sheet copper. It consisted of two semi-circular discs each of which made contact with one of the wires. These discs were kept separated a distance of about 1.0 mm. by an insulating block to which they were bolted. The disc and insulator assembly was fastened to a rigid wooden frame which was also fitted on the Lecher wires. Thus the metallic bridge and frame moved along as one body. Besides adding rigidity to the copper discs, this wooden frame served the further purpose of acting as a carriage for the device used in detecting the current maxima (thermo-couple or crystal detector).

A rear view of the bridge, the carriage, and the thermo-couple is shown in figure 15. The dimensions of the bridge discs are given in the sketch in figure 16a, and the various bridge connections used are represented in figures 16b, 16c, and 16d.

The set-up indicated in diagram 16b proved to be the most satisfactory, although that shown in figure 16c was the most
All dimensions are in centimeters. Not drawn to scale.

Figure 16.
sensitive. The arrangement represented in figure 16d was only used when the Lecher wires were connected directly to the grid and plate electrodes, and consequently had a high D.C. potential difference between them. Due to the difficulty experienced in keeping the crystal detector in proper adjustment, the bridge connection shown in figure 16c was seldom used. Binding posts were provided on the copper bridge disc so that a change from one thermo-couple to another, or to a crystal detector could readily be made.

The positions of current maxima were found by sliding the bridge along the wires and noting the places at which maximum deflections of a galvanometer, that was connected to it, occurred. This galvanometer had a sensitivity of $4,40 \cdot 10^{-7}$ Amp./cm. deflection; a resistance of 21.0 ohms, and a period of 7.0 seconds. The bridge and galvanometer were connected by means of flexible leads.

A calibration curve showing the galvanometer deflections as a function of the current passing through the thermo-couple bridge is shown in figure 17. This was used in determining the effective current at certain maxima on the Lecher wires.

A simple mechanical system was designed for sliding the bridge along the Lecher wires. This consisted of two wooden pulleys that were mounted just beyond the ends of the wires and over which a strong cord was passed. The ends of this cord were tied to the front and back of the bridge. By turning one of the pulleys, the portion of the cord on one side of the
CALIBRATION CURVE OF THERMO-COUPLE AND GALVANOMETER

HEATING CURRENT (MILLI-AMPERES)

Figure 17.
bridge was tightened and consequently the bridge was made to move. A long rod forming the shaft of the pulley located at the oscillator end of the Lecher wires was arranged to be turned by the operator. This is shown quite clearly in figure 18a. The circular handle on the rod is seen just above one of the rheostats.

* * * * * *

Most of the apparatus that was used in this investigation is shown as it actually appeared in the course of the tests in figures 18a and 18b.

E. Method of Procedure.

Before any tests could be made on the Barkhausen-Kurz oscillator, the triode employed in it had to be evacuated. This was done by means of a mercury vapor pump, of the type described by L. Langmuir (51), backed by a "Cenco Hyvac" pump. These were ordinarily set into operation at least six hours before any test was to be made, and were kept running during its entire course.

In view of the fact that accurate wave-length measurements were dependent upon a good contact between the bridge discs and the Lecher wires, the latter were cleaned just before starting a test. This was done by polishing them with fine sand-paper. The grit remaining on the wires after this operation was removed by wiping them with a moist cloth.
The practice of lighting the filament of the Barkhausen-Kurz oscillator triode and applying the grid and plate potentials to it several minutes before any readings were taken was followed. This permitted the filament rheostats, and the plate circuit potentiometer to reach an almost constant temperature with the result that a minimum number of adjustments of these controls was necessary in the course of the first tests.

The small continuous wave oscillator employing the UX201-A valve ordinarily required no special attention. If it did not oscillate when the filament was lighted and the plate potential applied, this state could generally be brought about by increasing the capacity of the blocking condenser. It was sometimes necessary, however, to increase the plate potential and augment the filament current. The chief difficulty experienced with this transmitter was the short life of the tubes as oscillators. This was probably due to the high emission currents required.

The magnitude of the current at resonance points of the bridge was sometimes sufficiently great to cause galvanometer deflections beyond the range of the scale. Since conditions under which this would occur were not known beforehand, it was found worth-while, before making a new test, to slide the bridge from one end of the Lecher wires to the other and observe the displacements. Whenever these proved to be excessive, the current passing through the galvanometer would be reduced by applying a shunt to the bridge, or by using a less sensitive detecting device.
C. Results.

1. Factors determining the wave-length of oscillations.

a. Potential differences between grid and filament. According to the theory advanced by Barkhausen and Ehr, the oscillations discovered by them are caused by a purely mechanical, backward and forward motion of electrons about a positively charged grid. One may therefore expect, assuming that the theory is correct, that any factor which will cause a change in this oscillatory movement will, in some way, affect the oscillations. An increased grid potential would constitute such a factor, since it results in an increased velocity of the electrons. This would affect a shortening of their time of travel from the filament through the grid to the reversal point that is determined by the grid and negative (or zero) plate potentials, and back to the filament. An electrical oscillation is produced by such a movement, and its period is equal to this time. It is thus perceived that an increase in grid potential should be attended by a diminished period of electrical oscillation, and consequently a lowering in the wave-length of the propagated disturbance.

Curves showing the wave-length as a function of the grid potential appear in figure 19. These were plotted from data obtained during tests in which the grid voltage was varied, and the plate potential and grid current were held at certain constant values. They indicate that the wave-length is decreased
Barkhausen - Kurz Oscillator Characteristics.
Grid Current Held Constant at 14 M-A.

WAVE LENGTH (METERS)

0.5

0

0.5

1.0

1.5

2.0

0

50

100

150

200

250

300

350

GRID POTENTIAL (VOLTS)

Figure 19.
in a regular manner as the grid potential is increased. In view of the fact that the grid current instead of the total emission current (sum of grid and plate currents) was held constant in obtaining the data for these curves, a slight error was introduced into those corresponding to plate voltages of -10.0 volts and 0.0 volts. The plate current was negligible in comparison with that in the grid circuit for the others. If the emission current had been held constant, slightly longer wavelengths would have been obtained in the case of the first-mentioned curves.

A wave-length—grid potential curve for which the emission current and plate voltage had been held constant is shown in figure 20. Above it are drawn two curves, one representing the wave-lengths calculated by Scheibe's formula (3), and the other those obtained from the formula of Barkhausen and Kurlz (3-1). In both cases, the calculated results were higher than the observed. For the greater part of the grid voltage range, however, the difference between the experimentally determined wave-lengths and those found from Scheibe's formula is quite small. Since the wave-length expression that was derived by Barkhausen and Kurlz is only valid for triodes having plane electrodes and uniform fields between them, it is hardly to be expected that the results obtained from it would agree quantitatively with those experimentally determined in this case.
Barkhausen-Kurz Oscillator Characteristic

Emission Current = 14.5 mA
Plate Potential = 0 Volts

Figure 20.
b. Potential difference between plate and filament. By making the plate potential lower than that of the filament, a zero potential surface can be established in the grid-anode space of a Barkhausen-Kurz oscillator triode. Since the kinetic energy of the oscillating electrons will be zero when they reach this surface, they will reverse their direction of travel at it and move back toward the grid. Thus the distance over which they travel in the grid-anode space may be varied by changing its location. This may be done by altering the value of the negative plate potential. If this distance is shortened and other factors remain unchanged, the period of oscillation of electrons will be decreased. As stated before, this will result in a reduction in the wave-length of the electric oscillations. Thus, according to the Barkhausen-Kurz theory, an increase in the negative value of the plate potential should be attended by a decrease in wave-length.

Curves showing the wave-length as a function of the negative plate potential appear in figure 21. They indicate, as had been predicted from theoretical considerations, that the wave-length decreases as the negative value of the plate potential increases. In obtaining the data for them, the grid voltage and current were held constant. The plate current, however, was not a negligible part of the total emission in the -10.0 volt to 0.0 volt range of plate potentials; consequently the wave-lengths in this region are slightly shorter than those which would have been obtained had the emission current remained
BARKHAUSEN—KURZ OSCILLATOR CHARACTERISTICS
GRID CURRENT HELD CONSTANT AT 14 M-A.

GRID VOLTS = 150
GRID VOLTS = 200
GRID VOLTS = 250
GRID VOLTS = 350

WAVE LENGTH (METERS)

NEGATIVE PLATE POTENTIAL (VOLTS)

Figure 21.
fixed.

Two rather interesting curves that show the manner in which the wave-length varied for small positive plate potentials appear in figure 22. The portions designated by A and B are continuations of the curves occurring on the negative potential side of the ordinate axis. Between A and A', and B and B' rather sharp breaks exist. In the regions indicated by dotted lines oscillations could be detected, but, due to their instability and irregularity, no definite data regarding them could be ascertained. Beyond these, stable oscillations of a relatively longer wave-length again appear. The new oscillatory ranges for grid potentials of 150 volts and 200 volts are represented by A' and B' respectively. These regions of longer waves, however, are extremely narrow. The oscillations whose wave-lengths are plotted in A' appear at a positive plate potential of slightly less than 2.0 volts and vanish abruptly at about 6.0 volts; those designated by B' likewise appear at about 2.0 volts but cease to exist at approximately 4.5 volts. For higher plate voltages, no oscillations could be detected.

The data for these curves are given in table III. The plate voltages recorded there, however, represent the readings of the plate voltmeter. In order to obtain the actual potential of the plate, it is necessary to subtract the voltage drop caused by the resistance in the plate circuit (80 ohms) from these.

By taking into consideration the effect of the alternating
Barkhausen-Kurz Oscillator Characteristics

Emission current held constant at 13.6 mA.

For curves A and A', grid voltage = 150 V.
For curves B and B', grid voltage = 200 V.

Positive Plate Potential (Volts)

Figure 22.
grid-plate voltage on electron movements, it would be possible to account for the curve portions A and B of figure 22. However, the portions $A'$ and $B'$ appear inexplicable on the basis of the Barkhausen-Kurz theory. The reappearance of oscillations on a longer wave-length, after a region in which they were unstable had been passed, would seem to indicate that the mechanism of these last appearing is different in some respects from that which causes the normal type.

a. Emission current from the filament. It is a well known fact that when a positively charged electrode surrounds a hot filament, some of the electrons emitted by the latter will be drawn to it. The others, however, will remain in the vicinity of the filament and will form a negative space charge.

The effect of this space charge in a Barkhausen-Kurz oscillator triode is to move the zero potential surface, which would otherwise occur at the filament, out toward the grid. Since the oscillating electrons are regarded as only being able to move up to such surfaces, this will cause their distance of travel in the grid-cathode space to be shortened. By an analysis similar to that employed in the case of negative plate potentials, it may be shown that this will result in a reduction in the wave-length of electric oscillations. The extent of this reduction will, of course, depend upon the number of electrons forming the space charge. Since an accumulation of electrons may occur at the plate, a further lessening of the wave-length is to be expected from this source. In explaining the
deviations between their observed and calculated results, Barkhausen and Kurz considered the effect of both the filament and plate space charges.

Curves plotted between wave-length and emission current (sum of grid and plate currents) will illustrate the effect of space charges on the former. Two such curves are shown in figure 23. The one designated by A shows that the wave-length is shortened by an increased emission current, that is, by a greater space charge; curve B, on the other hand, indicates that the two quantities are independent of each other. In A, however, the grid potential was held constant at 100 volts while in B it was fixed at 150 volts; the plate potentials were held constant at 0.0 volts in both cases.

* * * * *

The data from which the curves in figures 19, 20, 21, 22, and 23 were plotted are recorded in tables I, II, III, and IV. The plate currents in the tests made at plate voltages of -50, -40, and -30 volts were less than 20 micro-amperes.
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<th>Grid Current</th>
<th>Plate Current</th>
<th>Filament Voltage</th>
<th>Filament Current</th>
<th>Wave Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>0.0</td>
<td>11.0</td>
<td>2.60</td>
<td>5.54</td>
<td>4.06</td>
<td>210.7</td>
</tr>
<tr>
<td>150</td>
<td>+1.0</td>
<td>10.8</td>
<td>2.60</td>
<td>5.22</td>
<td>3.90</td>
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</tr>
<tr>
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<td>10.9</td>
<td>2.70</td>
<td>4.91</td>
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</tr>
<tr>
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<td>+2.0</td>
<td>10.5</td>
<td>2.60</td>
<td>4.91</td>
<td>3.80</td>
<td>257.5</td>
</tr>
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<td>4.91</td>
<td>3.80</td>
<td>254.0</td>
</tr>
<tr>
<td>150</td>
<td>+3.0</td>
<td>9.8</td>
<td>3.60</td>
<td>5.15</td>
<td>3.90</td>
<td>252.5</td>
</tr>
<tr>
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<td>+4.0</td>
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<td>4.50</td>
<td>5.15</td>
<td>3.90</td>
<td>257.3</td>
</tr>
<tr>
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<td>5.33</td>
<td>3.96</td>
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</table>

<table>
<thead>
<tr>
<th>Grid Volts</th>
<th>Plate Volts</th>
<th>Grid Current</th>
<th>Plate Current</th>
<th>Filament Voltage</th>
<th>Filament Current</th>
<th>Wave Length</th>
</tr>
</thead>
<tbody>
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<td>3.80</td>
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<td>4.94</td>
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</tr>
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<td>4.95</td>
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<td>214.0</td>
</tr>
<tr>
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<td>3.6</td>
<td>4.95</td>
<td>3.80</td>
<td>212.0</td>
</tr>
<tr>
<td>200</td>
<td>+4.0</td>
<td>9.0</td>
<td>4.6</td>
<td>4.95</td>
<td>3.80</td>
<td>218.0</td>
</tr>
<tr>
<td>200</td>
<td>+5.0</td>
<td>8.0</td>
<td>6.4</td>
<td>4.95</td>
<td>3.80</td>
<td>215.0</td>
</tr>
</tbody>
</table>
### Table IV.

<table>
<thead>
<tr>
<th>Grid Voltage</th>
<th>Plate Voltage</th>
<th>Current</th>
<th>Filament Voltage</th>
<th>Current</th>
<th>Wave Length</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0</td>
<td>5.0</td>
<td>4.65</td>
<td>3.60</td>
<td>255.2</td>
</tr>
<tr>
<td>100</td>
<td>0</td>
<td>5.0</td>
<td>4.55</td>
<td>3.55</td>
<td>254.3</td>
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<td>0</td>
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<td>255.0</td>
</tr>
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<td>3.74</td>
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<td>0</td>
<td>10.0</td>
<td>4.53</td>
<td>3.75</td>
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<td>11.0</td>
<td>4.33</td>
<td>3.78</td>
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</tr>
<tr>
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<td>12.0</td>
<td>4.33</td>
<td>3.80</td>
<td>247.4</td>
</tr>
<tr>
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<td>4.0</td>
<td>4.30</td>
<td>3.59</td>
<td>210.2</td>
</tr>
<tr>
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<td>0</td>
<td>5.0</td>
<td>4.30</td>
<td>3.55</td>
<td>210.4</td>
</tr>
<tr>
<td>150</td>
<td>0</td>
<td>6.0</td>
<td>4.30</td>
<td>3.60</td>
<td>211.6</td>
</tr>
<tr>
<td>150</td>
<td>0</td>
<td>7.0</td>
<td>4.56</td>
<td>3.65</td>
<td>212.0</td>
</tr>
<tr>
<td>150</td>
<td>0</td>
<td>8.0</td>
<td>4.64</td>
<td>3.66</td>
<td>210.0</td>
</tr>
<tr>
<td>150</td>
<td>0</td>
<td>9.0</td>
<td>4.72</td>
<td>3.70</td>
<td>209.0</td>
</tr>
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<td>10.0</td>
<td>4.90</td>
<td>3.74</td>
<td>211.0</td>
</tr>
<tr>
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<td>11.0</td>
<td>4.87</td>
<td>3.76</td>
<td>211.0</td>
</tr>
<tr>
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<td>0</td>
<td>12.0</td>
<td>4.88</td>
<td>3.77</td>
<td>209.9</td>
</tr>
<tr>
<td>150</td>
<td>0</td>
<td>13.0</td>
<td>4.94</td>
<td>3.80</td>
<td>207.1</td>
</tr>
</tbody>
</table>
2. Factors influencing the intensity of the oscillations.

a. Emission current from the filament. The intensity of the electric oscillations may be expected to increase if the number of electrons that form the aggregation oscillating about the grid is increased. This would result in the collection of more at the grid and plate electrodes. Since these electrons have proper phase relations for sustaining the excited oscillations, any addition to their number will cause a greater oscillatory power to be developed. This may be demonstrated experimentally by increasing the emission current, and measuring the oscillatory current in a resonant circuit that is loosely coupled to the oscillator.

A curve for which the data were secured in this way is shown in figure 24. It illustrates quite well how the intensity of oscillations varies with emission current.

The data for this curve were obtained in the course of the second test recorded in table IV, that is, when the grid potential amounted to 150 volts. In this case, the oscillatory current represents that which flowed through the thermo-couple bridge when the latter was at the second position of resonance on the Lecher wires. The location of this point of resonance varied less than 2.0 cm. for the whole range of emission currents. Effective values of the oscillatory currents were obtained from the galvanometer deflections by means of the calibration curve given in figure 17.
INTENSITY OF THE OSCILLATIONS
(MILLI-AMPÈRES)

Emission Current (Milli-Ampères)

Figure 24.

Barkhausen–Kurz Oscillator Characteristic
Data pertaining to the curve are recorded in table V. The figures tabulated in the column entitled "Distance to Bridge" represent the distances from a fixed point near the open end of the Lecher wires to the bridge when it occupied the second position of resonance.

Studies of Barkhausen-Kurz oscillators made by other experimenters have yielded the fact that the plate current forms a good standard by which the intensity of oscillations may be measured. From the data in table IV, it may be seen that it does increase quite steadily as the emission current becomes greater.

<table>
<thead>
<tr>
<th>Emission</th>
<th>Galvanometer</th>
<th>Oscillatory</th>
<th>Wave-</th>
<th>Distance to Bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current</td>
<td>Deflection</td>
<td>Current</td>
<td>Length</td>
<td>M.A.</td>
</tr>
<tr>
<td>-----------</td>
<td>-------------</td>
<td>---------</td>
<td>--------</td>
<td>-----</td>
</tr>
<tr>
<td>H.A.</td>
<td>CM.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.17</td>
<td>0.67</td>
<td>0.955</td>
<td>210.2</td>
<td>143.6</td>
</tr>
<tr>
<td>5.10</td>
<td>1.47</td>
<td>0.510</td>
<td>210.4</td>
<td>143.4</td>
</tr>
<tr>
<td>6.60</td>
<td>2.60</td>
<td>0.325</td>
<td>211.6</td>
<td>143.7</td>
</tr>
<tr>
<td>7.40</td>
<td>4.25</td>
<td>0.250</td>
<td>212.0</td>
<td>147.3</td>
</tr>
<tr>
<td>9.20</td>
<td>6.25</td>
<td>1.080</td>
<td>210.0</td>
<td>147.4</td>
</tr>
<tr>
<td>10.64</td>
<td>8.00</td>
<td>1.373</td>
<td>209.0</td>
<td>147.7</td>
</tr>
<tr>
<td>12.00</td>
<td>11.70</td>
<td>1.465</td>
<td>211.0</td>
<td>147.5</td>
</tr>
<tr>
<td>13.40</td>
<td>15.30</td>
<td>1.630</td>
<td>211.0</td>
<td>147.8</td>
</tr>
<tr>
<td>14.60</td>
<td>19.50</td>
<td>1.910</td>
<td>209.8</td>
<td>146.7</td>
</tr>
<tr>
<td>16.10</td>
<td>24.40</td>
<td>2.145</td>
<td>207.1</td>
<td>146.8</td>
</tr>
</tbody>
</table>
b. External circuit, and the elements affecting the wavelength. In his study of Barkhausen-Kurz oscillators, A. Scheibe (76) found that the oscillation intensity was greatly influenced by the constants of the external circuit. He showed the effect of the latter in curves plotted between intensity of oscillations and negative plate potentials. These possessed extremely sharp maxima. For external oscillatory circuits having different constants, the maxima occurred in different positions. This appears to indicate that when some definite ratio exists between the period of oscillation of electrons and that of the external oscillatory circuit, the intensity of the oscillations will be a maximum.

In order to determine whether the external oscillatory circuit had any effect upon the oscillations, the lengths of the conductors forming it were changed. For this purpose, two pieces of No.8 B. and S. gauge copper wire that were 35.0 cm. long were added to the conductors already connected to the grid and plate electrodes.

This was found to cause a diminution in the intensity of the oscillations. The galvanometer deflections at corresponding resonance positions of the bridge before and after the 35.0 cm. lengths of wire were added are as follows:

<table>
<thead>
<tr>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.90</td>
<td>1.20</td>
</tr>
<tr>
<td>11.10</td>
<td>2.05</td>
</tr>
</tbody>
</table>
In this test the grid and plate potentials were 150 volts and
0.0 volts respectively; the emission current was 15.2 milli-
amperes, and the wave-length was about 210 cm. Similar results
were obtained in a test made at a grid potential of 200 volts.

This indicates that the intensity of the oscillations may
be varied by altering the external circuit.

A general notion as to the manner in which the oscillation
intensity varies with the wave-length may be gained from the
plate current data in table II. These indicate that the most
intense oscillations were produced on wave-lengths lying be-
tween 211 cm. and 254 cm.

3. Beats between the Barkhausen-Kurz oscillator and the normal
continuous wave oscillator.

Since the Barkhausen-Kurz oscillator was capable of pro-
ducing oscillations whose wave-lengths were greater than those
developed by the continuous wave oscillator, when the latter was
operating near its upper frequency limit, it was possible to de-
termine whether beats could be obtained between them. This
could be done by impressing alternating potentials from both
sets upon a detector having a curved current-voltage character-
istic. Instead of using a separate detector for this purpose,
however, it was found possible to employ the continuous wave
oscillator as both a local generator and receiving set. Re-
ception was effected by means of a loud-speaker that was con-
ected in series with the plate battery (figure 10). This set-
up then formed a receiver similar to the type described by
0. Cords (7).

After the two oscillators had been adjusted to approximately the same frequency, they were inductively coupled. Final tuning then had to be done by varying the grid potential of the triode in the Barkhausen-Kurz set.

Beats of audible frequency were obtained when the frequencies of the two oscillators differed by a few thousand cycles. The note produced by them in the loud-speaker, however, did not sound pure. It might be described to some extent by stating that it appeared highly modulated. Whether this was caused by variations in amplitude of the Barkhausen-Kurz oscillations or by some other agency could not be determined.

The approximate wave-lengths on which the two oscillators were operating when beats were obtained occurred in the vicinity of 2.7 meters.


The effect of the external circuit on the wave-length of oscillations was investigated by changing its capacity and inductance. In the case of the capacity, this was done by placing two rectangular copper plates (7.0 cm. x 3.2 cm.), whose common separation was 1.9 cm., across the parallel portion of the antennas that were connected to the grid and plate electrodes. The inductance was altered by adding 35.0 cm. lengths of No. 8 B. and S. gauge copper wire to each of the two conduc-
tors which formed the external oscillatory circuit. These mod-
ifications, however, produced only slight changes in the ob-
served wave-lengths.

In two tests that were made at different plate voltages,
and with and without the additional capacity in the external

circuit, the following wave-lengths were obtained:

<table>
<thead>
<tr>
<th>With Additional Capacity cm.</th>
<th>Without Additional Capacity cm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>210.6</td>
<td>211.2</td>
</tr>
<tr>
<td>177.6</td>
<td>176.9</td>
</tr>
</tbody>
</table>

The first of these tests was made with grid and plate poten-
tials of 150 volts and 0.0 volts respectively, and a constant
emission current of 14.6 milli-amperes; in the second, the grid
potential was again equal to 150 volts, but that of the plate
was set at -20.0 volts. The emission current in the second
case amounted to about 14.1 milli-amperes.

Somewhat similar results were obtained when the inductance
of the external circuit was increased by adding the 35.0 cm.
lengths of wire to it. In a test made with grid and plate po-
tentials of 150 volts and 0.0 volts respectively, and an emis-
sion current of 13.2 milli-amperes, the following wave-lengths
were obtained:

<table>
<thead>
<tr>
<th>With Additional Inductance cm.</th>
<th>Without Additional Inductance cm.</th>
</tr>
</thead>
<tbody>
<tr>
<td>210.0</td>
<td>208.0</td>
</tr>
</tbody>
</table>
These results indicate that the frequency of Barkhausen-Kurs oscillations is not determined by the constants of the oscillatory circuit that is connected to the grid and plate electrodes.

When the Barkhausen-Kurs oscillator was operating on the shorter wave-lengths (1.18m. to 1.50m.), oscillations of the type known as "dwarf waves of the first order" were detected. These were of very nearly the same intensity as the normal waves though of roughly twice as great a frequency.

While making wave-length measurements with the Lecher wires, the current maxima caused by these dwarf waves could sometimes be quite easily distinguished from those produced by normal oscillations. A case in which this happened is illustrated by the data in table VI. The figures in the column entitled "Distance to Bridge" represent the distances from a fixed origin to the successive points at which resonance occurred. Under the heading "Galvanometer Deflections", readings are given which constitute a measure of the current which flowed through the thermo-couple bridge. The two classes of waves designated by A and B were the current maxima caused by the normal oscillations while those represented by C were produced by the dwarf waves. The data in this table were obtained in the course of a test made at grid and plate potentials of 350 volts and -50.0 volts respectively, and with an emission current of 14.0 milli-amperes.
Table VI.

<table>
<thead>
<tr>
<th>Class</th>
<th>Distance to Bridge</th>
<th>Deflection</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>22.0</td>
<td>1.25</td>
</tr>
<tr>
<td>A</td>
<td>31.7</td>
<td>2.70</td>
</tr>
<tr>
<td>C</td>
<td>51.6</td>
<td>2.05</td>
</tr>
<tr>
<td>B</td>
<td>60.6</td>
<td>2.50</td>
</tr>
<tr>
<td>C</td>
<td>81.0</td>
<td>2.10</td>
</tr>
<tr>
<td>A</td>
<td>91.0</td>
<td>2.65</td>
</tr>
<tr>
<td>E</td>
<td>121.0</td>
<td>2.30</td>
</tr>
</tbody>
</table>

It may be seen from these data that the distance between consecutive maxima of the C class is about 29.5 cm, while that between the A type (or the B type) is approximately 60.0 cm. This indicates that the dwarf waves were about one-half as long as the normal oscillations.
IV. ANALYSIS OF RESULTS.

If the electric oscillations are regarded as being produced by a back and forth movement of electrons about a positively charged grid, in accordance with the hypothesis advanced by Barkhausen and Hurs, most of the results obtained in this investigation may be readily explained. Under such conditions, any modification of the motion of electrons would be attended by some change in the electric oscillations. The effect of various modifications will be qualitatively explained in the following analyses.

In figure 19, the curves show that the wave-length of oscillations decreases as the grid potential increases. This can be accounted for from the fact that the electrons are made to move with greater velocities at the higher potentials. Since the period of the electric oscillations is equal to the time required by the electrons to perform one complete oscillation about the grid, this time will be decreased if the movement is executed at a higher speed. Thus the wave-length will be shortened since it is directly proportional to the period.

A comparison between calculated wave-lengths and those determined experimentally is shown in figure 20. In this case it is seen that a fairly good agreement exists. The formulae used in these calculations were derived from expressions for electron velocities when the electrons are moving under the influence of various electrode potentials. Probably the greatest cause for the observed wave-lengths being shorter than the cal-
culated in the space charge in the vicinities of the filament and plate. This would tend to reduce the distance over which electrons move in both the filament-grid and grid-plate spaces. Since its effect would be most pronounced at the lowest grid voltages, the greatest error should occur at this extreme of the wave-length—grid potential characteristic. The curves indicate that such is the case.

If the plate of a Barkhausen-Kurz oscillator triode is made negative relative to the filament, the distance over which electrons will travel in the grid-anode space will be shortened. This will cause the period of oscillation of electrons about the grid to be diminished, and as a result, the wave-length will be reduced. Curves showing the manner in which this occurs are given in figure 31.

When positive potentials are applied to the plate, the characteristics given in figure 22 are obtained. These show rather abrupt breaks which apparently form transition regions between normal Barkhausen-Kurz oscillations and some new type. The longer wave oscillations, that is, those occurring in the ranges designated by A' and B', do not seem to be explainable by means of the Barkhausen-Kurz theory unless secondary emission of electrons at the plate is assumed. In the event that such a situation exists, the necessary increase in period might be accounted for by a lateral movement of the electrons before starting on their journey to the grid.

Curve A of figure 23 shows the manner in which space
charges in the vicinities of the filament and plate shorten the wave-length. These regions have an effect that is equivalent to moving the zero potential surfaces that occur in the filament-grid, and grid-plate spaces toward the grid. This, of course, causes a reduction in the wave-length of the electric oscillations, because the electrons oscillating about the grid have shorter distances over which to travel.

The curve in figure 24 indicates that the intensity of the oscillations is almost directly proportional to the emission current. This may be explained by regarding the increased emission as having caused more electrons to enter the group that oscillated about the grid. An increase in the electrons in this group results in a greater number being collected by the grid and plate, and since their phase relations are correct, they add to the oscillation intensity.

The variations in oscillation intensity that were observed when the frequency was altered were found to be caused by the external oscillatory circuit. This became apparent when changes were made in its constants, and measurements were carried out under identical conditions of applied voltages and emission currents. Since these modifications changed the natural period of oscillation of the circuit, its influence upon the electron oscillations became greater or less depending upon the new ratio of the periods of the two. A. Schaeibe (76) showed quite conclusively that when the external circuit was tuned to the frequency of the oscillations produced by the triode, maximum in-
tensity occurred.

The fact that the beats which were obtained between Barkhausan-Kurz oscillations and those produced by a normal continuous wave oscillator appeared highly modulated, precludes the conclusion that the former are continuous in all respects. However, the manner in which this experiment was performed did not make it unlikely that some outside agency could cause these modulations. In fact, this could easily have happened since the high potential batteries supplying the two oscillators were also connected to other loads. It is thus apparent that a further study of the beats, made under more ideal conditions, is necessary before any definite conclusions may be drawn from them.
While the results thus far obtained between Bermudan and
Kumamoto are interesting and prove profound

...
wave oscillator appeared to be highly modulated, a conclusion that this was due to the former is not warranted. Probably as good a method as any for determining whether the Barkhausen-Kurz oscillations are continuous in all respects would be by making an oscillographic study of the beats.

In order to extend the Barkhausen-Kurz theory so that it may explain the longer wave oscillations that were observed when the plate was at a positive potential, it seems as though secondary emission of electrons from the plate must be assumed.

Since practically all the experimental results that were obtained could readily be explained by means of the Barkhausen-Kurz theory, it seems reasonable to suppose that the actual mechanism of the oscillations is as described by these men.
VI. SUMMARY.

The investigation that is reported in this thesis was undertaken in an attempt to obtain more information concerning Barkhausen-Kurn oscillations. For the production of these, a specially designed, three-electrode vacuum tube was built.

The study was mainly concerned with determining the effect of grid and plate potentials, emission current, and external circuit constants on the wave-length and intensity of oscillations.

From the experimental results, it was found that:

1. Increased grid potentials caused the wave-length to be shortened.

2. Increased negative values of plate potential were attended by reductions in the wave-length.

3. A rather abrupt change to longer wave-lengths occurred when a positive potential of a few volts was applied to the plate.

4. Increased emission currents effected a small decrease in wave-length.

5. Rather large changes in the constants of the external oscillatory circuit produced only slight changes in the wave-length.

6. Increased emission current caused the intensity of the oscillations to become greater.

7. Alterations of the constants of the external cir-
suit produced changes in the oscillation intensity.

As a part of the investigation, beats which were obtained between Barkhausen-Kurz oscillations and those produced by a normal continuous wave oscillator were studied.
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