ELECTRON OSCILLATIONS
IN
THERMIONIC VACUUM TUBES

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A THESIS

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by

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Preface

In recent years there have come into existence a large number of scientific subjects whose sole literature is contained in periodicals. They are not sufficiently developed to have become the subjects of text-books or even to have become included in texts on related topics. The problem of electron oscillations occupies this category. At most it has claimed half a dozen paragraphs in the most modern writings on Radio Communication.

The technical articles on this subject are quite extensive now, and probably total from three hundred to four hundred. But the matter has not proved so understandable that it could be settled once and for all by a single investigation. Practically the opposite is the case. Each investigation seems to differ, in many cases radically, from every other.

It has been my purpose in preparing the present thesis not essentially to attempt to contribute new material to the existing mass, but rather to digest all that is available, to bring out correlations where they seem to exist, and to apply experimental test to such aspects as appeared to justify it. In all, slightly over one hundred and fifty sources have been consulted and condensed. With very few exceptions these have been the originals, although about twenty-five have been at hand only in the form of abstracts.

The subject is not yet on a quantitative basis, and chiefly for that reason the various papers have not been dissected to allow grouping according to subject matter, but have been presented in fairly exact chronological order.

Papers dealing with range tests on communication and reception have not been discussed. The whole problem has been viewed from the physical rather than the practical or communication standpoint. If the detail gone into may seem too minute occasionally, it has been due to the fact of brevity not being considered an essential characteristic of a thesis.

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Chapter I

The Subject

1. Philosophical Considerations

While James Clerk Maxwell was an undergraduate student at Cambridge about the year 1850,he conceived the idea of translating the extraordinary electrical revelations of Michael Faraday into the expressive notation of mathematics. Many years passed before he possessed sufficient training to enable him to carry out this task,but he must have had it continuously in his mind.

Faraday's work had been the first indication of action at a distance,of an obscure relation between a cause and an effect. Faraday himself had been highly dissatisfied with the simple explanations of the phenomena he observed,and Maxwell was even more so. It became his principal ambition to overturn the idea of "action at a distance" and to substitute in its place a physical and mathematical explanation of inductive and radiative phenomena.

Twenty-three years later,with the appearance of his "Treatise on Electricity and Magnetism",his ambition was fully realized. It involved the greater part of his life work. In general,it demonstrated that all electrical and magnetic phenomena could be reduced to states of stress or motion in some undefined material medium. Induction or radiation became simply a question of propagation of effects through this medium.

Maxwell's work was so thorough and so fundamental that even today it remains the absolute mathematical basis of all our electromagnetic theory. It has been described as "one of the most splendid monuments ever raised by the genius of a single individual."

Over one hundred years before the time of Maxwell, the Newtonian and the Hughens schools of physicists had waged their battle as to the mechanical nature of light, and chiefly from the results of experiments on polarisation and interference had finally reached the definite conclusion that light was transmitted by harmonic vibratory motion in some all-pervading "aether". Maxwell's mathematical researches, which made evident to him the propagation of such harmonic vibrations if they were electro-magnetic in character, necessarily had led him to the prediction of the electro-magnetic nature of light as early as 1864, and his equations postulated that the velocity of such a propagation must numerically equal the ratio of the electro-static and electro-magnetic systems of units. Within the limits of experimental accuracy, this latter statement has of course been verified and light is indisputably recognized as an electro-magnetic phenomenon. The wavelengths of an oscillatory light had been determined in Huyghen's time, and were fairly accurately known. On the assumption of Maxwell's predicted value of the velocity, therefore, it was immediately possible to calculate the limiting frequencies of light, and these were found to be about 9×10^{14} cycles per second and 3×10^{14} cycles per second as upper and lower limits respectively.

But Maxwell's theory was not confined to this explanation of the nature of light. Its mathematics were not a function of frequency. In Maxwell's mind an experimentally observed frequency for red light of 3×10^{14} cycles per second was of no more importance than a physically non-existent oscillation of frequency 10 cycles per second, or 10^{1000} cycles per second. It was not therefore essentially either imagination or foresight that caused him to "prophesy" the discovery in the future of naturally or artificially produced electrical oscillations of frequencies widely different from those of visible light. It was merely in keeping with his convictions as expressed in his equations.

The potentialities of the prophecy were, nevertheless, tremendous. In the last sixty years of scientific development more and more physical phenomena have been shown to be electro-magnetic in nature until we now know of frequencies as widely different as 10,000 cycles per second and 10^{23} cycles per second, which can be produced artificially, or are present in Nature.

The relation between heat waves, infra-red, and red light waves was definitely established in the time of Maxwell, the wavelengths were known, and it was found that heat waves extended the electro-magnetic spectrum from the lower limit of the visible light range down to a frequency of 5×10^{11} cycles per second.

The next step was not made until 1888 when the researches of Hertz appeared, and proved the possibility of generating frequencies of the order of 10^7 cycles per second. Shortly before 1900 Röntgen demonstrated his X-rays, which supplied a band of frequencies centering around 10^{17} cycles per second.

Less than ten years later Ernest Rutherford found the gamma radiations from radio-active substances to be electro-magnetic waves, with a mean frequency of about 10^{19} cycles per second. The so-called "cosmic rays", which have been detected and investigated by Millikan and others, were first noticed not long after Rutherford's work, and extended the spectrum from 10^{19} to 10^{23} cycles per second. The final result by 1920, with the expansion of each of these frequency ranges as far as possible in either direction, was the electro-magnetic spectrum of Fig. 1.

It is experimentally as well as logically true that waves of the same frequency are inherently identical, regardless of how they are produced. There is no particular interest, therefore, in attempting to find new methods of generating any frequencies contained in the now continuous parts of the spectrum. Useful research may best be expended on the determination of the characteristics of waves which it is already possible to produce, or on the discovery of means for producing frequencies which are not contained in the known spectrum.

By 1920, Fig. 1 indicates that there were three frequency ranges in which oscillations were not known to exist. The first of these is the range from 0 hertz to 10^4 hertz*. Actually it is of course possible to generate any frequency from 0 hertz to

* The phrase "cycles per second" sounds rather awkward on continuous repetition. To supplant it and to perpetuate the name of the man, the term "hertz" has recently come to have this meaning, and will be used in that sense from this point on.

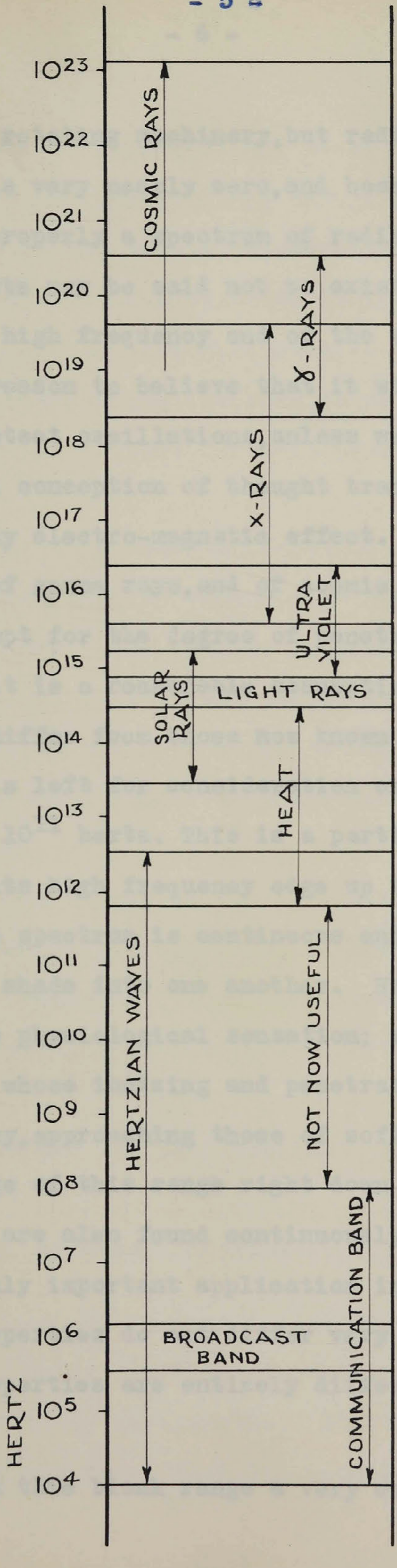


FIG. 1 ELECTROMAGNETIC SPECTRUM - 1920

10^4 hertz by rotating machinery,but radiation of power at such frequencies is very nearly zero,and because the electro-magnetic spectrum is properly a spectrum of radiations,the portion of it below 10^4 hertz may be said not to exist.

At the high frequency end of the spectrum,above 10^{23} hertz, there is no reason to believe that it will ever be possible to produce or detect oscillations,unless we sometime accept the philosophical conception of thought transference as an ultra high-frequency electro-magnetic effect. The characteristics of hard X-rays,of gamma rays,and of cosmic rays are very much the same except for the degree of penetrative power possessed by each and it is a reasonable assumption that higher frequency waves would differ from those now known only in this respect.

There is left for consideration only the range from 10^8 hertz to 5×10^{11} hertz. This is a particularly interesting range. From its high frequency edge up to the cosmic ray frequency,the spectrum is continuous and the various types of radiation shade into one another. Heat and infra-red light give the same physiological sensation; violet light shades into ultra-violet whose ionizing and penetrative properties increase with frequency,approaching those of soft X-rays. From the lower frequency edge of this range right down to the spectrum limit, oscillations are also found continuously. These radiations all have their only important application in communication work, and their properties do not differ very greatly with frequency. But these properties are entirely different from those of light or heat.

Thus in this blank range a very complete change in the physical characteristics of the waves takes place. A change in the method of propagation, a change in the method of detection, and a change in the method of generation. How it is possible for the properties of heat waves to shade into those of radio waves is a question that will best be solved by the generation of all the intermediate frequencies as continuous oscillations. The discovery of methods for this generation is a wide field of research.

Obviously the question could be approached from three sides. The intermediate frequencies might be produced by an extension of the known methods of generating and detecting heat radiations, or by an adaptation of radio oscillators of known type, or by the fortuitous method of finding a new means of producing oscillations whose frequency might lie in the desired range.

Strangely enough, it is this latter solution which has developed the most rapidly, and the entire subject of electron oscillations concerns itself with exactly this frequency range, or properly a limited part of it, from about 10^8 to 10^{10} hertz.

So much for the philosophical aspect.

2. Practical applications.

The story of successful long distance radio communication was for many years a straightforward narrative of communication at lower and lower wavelengths. Starting in the range of hundreds of meters, it was found that 100 meters was better, then 50 meters and finally 20 meters and 10 meters. But between the wavelengths of 10 and 20 meters the increase in the ratio of distance to power begins to fall off. It is found that at these shorter wavelengths a very much denser ionization of the upper atmosphere is required for reflection of the waves, and communication possibilities have a decided diurnal variation with the motion of the sun.

Very recent investigations indicate that no waves shorter than about 5 meters are ever reflected from the Heaviside layers and communication on wavelengths shorter than this critical value will be possible only by waves travelling in a direct line from the receiver to the transmitter.

Waves under three meters in length are propagated almost strictly linearly, and are absorbed by most material obstacles. At the same time they are short enough to permit the construction of reflecting devices having dimensions of the order of one or more wavelengths, which is a necessity for a satisfactory reflector.

Their future in the history of communication is very definitely defined by these characteristics. Three principal applications are indicated:

(1) Urban broadcast service. This use has already been demonstrated very satisfactorily for waves slightly above the three meter range, and there is no doubt that it can be extended down much farther. The general idea is to have a transmitter located at a central point in a district, designed to service only a range within a mile or less.

(2) Landline chain radio-telegraph service. Oscillators at these low frequencies are very economically built, and a logical development is the establishment of a chain of such stations between industrial centers, all the intermediate stations of the chain acting as relays.

(3) Secret communication. Even at the longer short waves companies operating commercial radio services have attempted to obtain a beam effect of transmission that would provide some degree of privacy. At wavelengths below 3 meters the transmission beam can be confined so closely that detection of signals at one degree or less off the line of the beam becomes impossible.

There is thus not the slightest doubt that transmission on frequencies between 10^8 and 10^{10} hertz is an important practical proposition, and will be developed rapidly when conditions warrant.

But this can never be possible until all the possibilities and vagaries of the equipment which is to be used have been thoroughly and clearly worked out, and this is certainly not yet the case for ultra-high frequency oscillators of any type. While ultra-high frequency equipment remains as unstable and as sensitive as it is at present, it has no future in communication.

When the subject becomes firmly established on a quantitative basis, so that desired results can be obtained by satisfying perfectly definite rules, commercial development can begin. Until then the subject remains entirely in the hands of the experimenter.

3. Early history.

Until the year 1918 the regenerative vacuum-tube oscillator was the only known means of producing continuous oscillations at the lower radio wavelengths. The lowest wavelength that had been reached by that time was of the order of 5 meters. A paper which we may consider as representative of the most advanced work of the period is one by W.C.White [1] which describes the production of thse shortest oscillations. By 1919 the lower limit had been pushed down as far as 1.5 meters, chiefly as a result of the work of Gutton and Touly in France [2]. Since then innumerable workers have tried their hands at the same problem, but with very little success in regard to generating lower wavelengths. A very thorough paper by C.R.Englund summarizes these efforts up to 1927, and lists 29 items of bibliography [3], while a recent paper by Commander W.H.Wenstrom deals briefly with the complete history [4] and also contains a large bibliography.

It seems evident from all these records that the regenerative oscillator will never be useful for dependable generation of wavelengths shorter than 1.5 meters, in spite of the fact that extreme cases have shown the possibility of producing waves as short as .60 meters.

Such oscillations are not "electron oscillations", and do not fall within the scope of the present thesis, so that no more space will be devoted to them at this point. A certain amount of experimental work was done on them in leading up to the main work of the thesis, and it will be mentioned later.

A second type of circuit for the production of high frequency continuous oscillations with a vacuum tube was first described by a paper by A.W.Hull [5] in 1918,which described the discovery of the negative resistance or dynatron characteristic of a triode. In general,using resonant circuits,it has not been possible to obtain oscillations at shorter wavelengths than about 15 meters with the dynatron circuit,but the underlying secondary emission principle has been found to have important bearings on the generation of electron oscillations. The development of this is discussed more fully in chapter IV.

In November of the following year there appeared in Radio Review a short paper by R. Whiddington. It told how, using a gassy vacuum tube in the circuit of Fig. 2 he had been able to detect and study oscillations whose wavelength,within the limits of observational accuracy varied with the voltage on the grid of the tube in such a way that the product of the grid voltage and the square of the wavelength was constant. The wavelength also appeared to be dependent on the dimensions of the tube,but had no relation whatever to the constants of any external circuit connected to the electrodes.

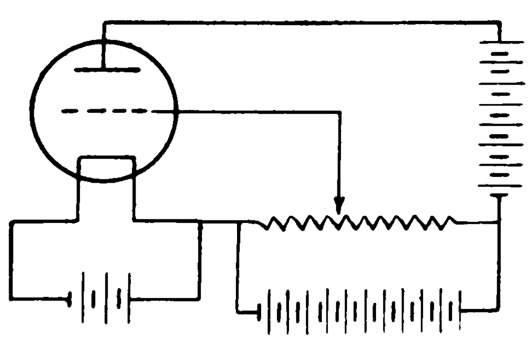


Fig. 2

By supposing the resistance of certain spots on the tungsten filament which for some reason,probably chemical,would be particularly sensitive to temperature changes,he worked out the following mechanism for the oscillations:

"Electrons emitted from such a spot will travel to the grid with a velocity u given by $\frac{1}{2} m u^2 = e V$, where V is the voltage on the grid with respect to the particular point on the filament. The electrons will thus take a definite and calculable time to travel from the filament to the grid under the potential applied. On passing through the grid, however, the electrons pass into the strong electric field of the anode and assume ionizing speed. The negative ions follow the electrons to the anode, but the positive ions pass back through the grid to the filament with a velocity u' determined from their mass m'. There will thus be a cloud of positive ions focussing on the filament and bombarding the original electron-emitting spot. This bombardment, by producing a new burst of electrons, sets up a self-sustaining current oscillation whose period is determined (for any particular valve) solely by the charge to mass ratio of the ions present and by the potential applied to the valve."

Because the ions present were the heavy ions of mercury vapor, the wavelengths he observed were of the order of 500 meters. He suggested the name IONIC oscillations as descriptive of the phenomenon.

Less than two months later the Physikalische Zeitschrifte presented a paper [7] under the title "The shortest waves that can be produced by vacuum tubes". The authors described experiments using a high vacuum tube in a circuit like that of Fig. 3. They had observed oscillations which, like those found by Whiddington, had their wavelength determined only by the dimensions of the tube electrodes and by the potentials applied.

In this case, though, there were no heavy ions present, and the oscillations had to be caused by the electrons from the filament of the tube. Consequently, the wavelengths were much lower than those Whiddington had found. They

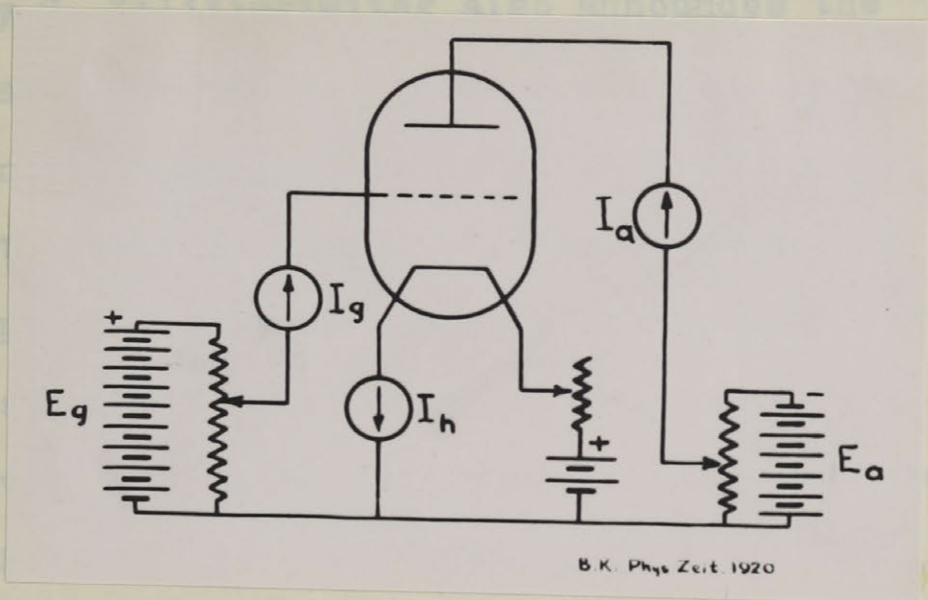


Fig. 3

were, in fact, of the order of 50 centimeters, and were beyond a doubt the shortest waves ever known to be generated by a triode up to that time. The authors coined the phrase ELECTRON oscillations as indicative of the method of generation.

This was the paper of H. Barkhausen and K. Kurz, and because of it the oscillations have come to be known in general as Barkhausen Kurz oscillations. According to them electron oscillations are:

Any oscillations generated by a vacuum tube, which maintain themselves purely by a repeated orderly motion of the electrons in the tube, which do not require for their maintenace or detection that any external circuit be applied to the electrodes of the tube, and whose wavelength is dependent primarily on the dimensions of the electrodes and the potentials applied to them.

Such, in general, is the meaning that will be implied by the phrase as used throughout the following pages. The next few chapters are a survey of the work that has resulted directly from this original paper of Barkhausen and Kurz.

It is worthy of note here that a paper published in 1921 [50] by S. Zilitinkiwitsk also announces the "discovery" of this same type of oscillations, and the work was evidently done entirely independently of that of Barkhausen and Kurz, although it appeared later. This paper and a second by the same author [51] appeared only in a Russian periodical (Archiv.f.Electrot.) which is not widely circulated. Neither of the two have been available in the original, and the only references found (Science Abstracts, 1926) give no indication of the technical contents. It is therefore unfortunately not known how fully the subject was investigated.

Chapter II

The Barkhausen Kurz Paper

The possibility of generating electron oscillations appears never to have existed as a theory before the experimental discovery of the fact. In fact the oscillations were originally detected as a disturbing influence in connection with other experiments on vacuum tubes, and were practically forced on the attention of the discoverers. For some time after there existence was first indicated, experimenting had to be done to find out what accounted for them, and how they might be produced as desired. Such at least is the opening confession of the authors of this paper.

The name of H. Barkhausen appears quite frequently in scientific literature, and this experimenter has been actively and successfully associated with a very diverse group of physical subjects. Probably for this reason, and because the discovery of the waves was accidental in nature, the original paper makes no attempt to expand very fully on their properties.

The circuit which was first used, and which is the basic circuit of all electron oscillators, is that of Fig. 3. Showing only the bare essentials, it consists of a triode tube whose electrodes are cylindrical in shape and are symmetrical with respect to the filament, a high potential battery with potentiometer and milliameter in the grid circuit, the same for a lower voltage and current in the plate circuit, and a heating battery with rheostat and ammeter in the filament circuit. If the tube is satisfactory, such a circuit will always serve to demonstrate the oscillations.

The measurement of wavelength by the formation of standing waves on conductors has been used as far back as the time of Hertz, and its accuracy and limitations are very well understood. C.R.Englund has traced its growth very thoroughly [8] and there is no doubt that by 1920 the method was universally recognized. At any rate, Barkhausen and Kurz immediately adapted it to their purpose.

Using two long parallel rods, one connected to the grid and the other to the plate of the tube, they observed with a detector the position of voltage nodes and loops and by measuring the spacing of these found the wavelength given by their first measurement to be exactly 100 centimeters. Continuing the same procedure, they obtained data for two curves indicating the effect of the potentials on the wavelength.

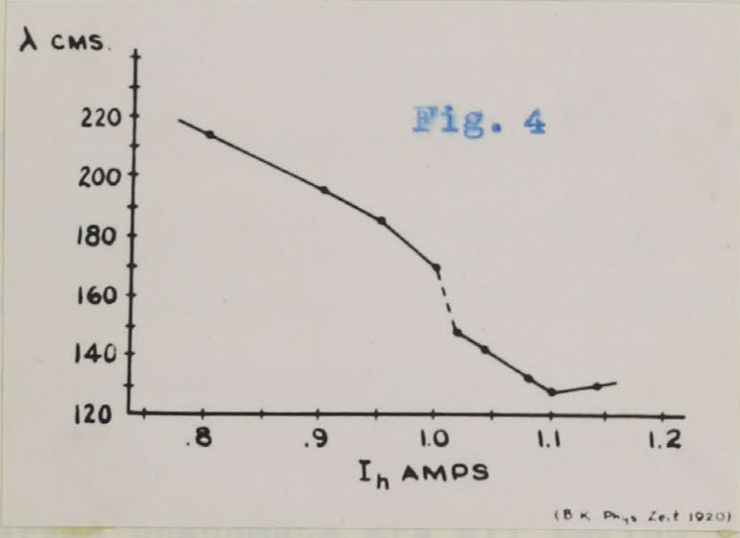


Fig. 4

The first of these, Fig. 4, is taken with a positive grid voltage of 180 and a negative plate voltage of 32.5, and indicates a very marked change of wave length with change of filament current. For the same curve the formula later developed would substitute a constant wavelength of 270 centimeters. In view of later work, the most interesting feature of this curve is its continuity over the wide filament current range. Only one slight break occurs, between 1.00 and 1.02 amperes.

The second characteristic, Fig. 5, indicates wavelength variation with increasing negative anode voltage, at constant filament current. The calculated curve shown is taken from the formula to be derived later. Here again the continuity of the curve is a feature that has been verified by very few other experimenters.

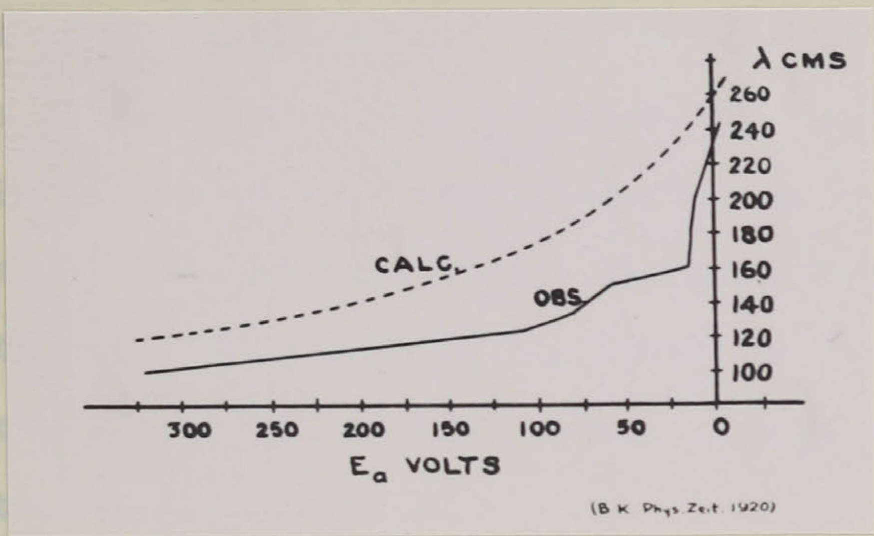


Fig. 5

The general observations made were the independence of the wavelength of any external circuit connected to the electrodes, the fact that no body capacity influences were present, and the indication that a definite relation existed between the oscillation intensity and the positive plate current flowing. The Schott M tube used has an anode diameter of 3.1 centimeters, a grid diameter of 0.7 centimeters, and a normal filament current of 1.0 amperes.

"From these observations, the indication is that the observed phenomena are all taking place inside the tube, and that the maintenance of the oscillations must be determined by a motion of the electrons; the following theory would appear to be not unlikely.

The electrons leaving the filament are drawn with considerable velocity to the grid. Here a small part of them strike the grid wires, but by far the greater part pass through the spaces between the wires and approach the plate. This may be easily demonstrated by the fact that even a low positive plate voltage suffices to make the anode current much greater than the grid current. If,however,the anode is negative,the electrons are unable to reach it; they are decelerated,reverse in direction,and return towards the grid. Here again only a small part of them strike the grid,the remainder continuing on through. Thus most of the electrons move back and forth through the grid,pendulum-like,before they finally strike it. This to-and-fro motion of the electrons produces the electric oscillations. For this to be true,it is necessary only that a semblance of order enter into the motion of the electrons, that they move in phase,and that this order be set up by the electrons themselves. In this way the oscillations will be self-starting."

Assuming plane electrodes and the anode at the same potential as the cathode,the wavelength may be easily calculated as follows: The velocity of an electron acted on by a voltage E_g is given by the formula $v = \sqrt{2 \frac{e}{m} E_g} = 6 \times 10^7 \sqrt{E_g}$, where e/m is the ratio of the charge to the mass for the electron. The ratio of this velocity to the velocity of light is

$$\frac{v}{v_o} = \frac{6 \times 10^7 \sqrt{Eg}}{3 \times 10^{10}} = \frac{\sqrt{Eg}}{500}$$

The reciprocal of this ratio,multiplied by the path traversed by the electron during one oscillation,should be equal to the wavelength of the oscillation. But the predicted length of the path is the distance from the filament to the plate and back to the filament; i.e.,twice d_a,the diameter of the anode. Thus

$$\lambda = 2\, d_a\, v_0/v = \frac{1000\, d_a}{\sqrt{E_g}}$$

With a negative anode voltage the electrons do not get as far as the anode. The calculated equivalent anode diameter is then

$$d'_a = \frac{d_a E_g - d_g E_a}{E_g - E_a}$$

so that in the most general case the wavelength is given by

$$\lambda = \frac{1000}{\sqrt{E_g}} \; \frac{d_a E_g - d_g E_a}{E_g - E_a}$$

The difference between the calculated and observed wavelengths in Figs. 4 and 5 is explained as due to the influence of space charge. For Fig. 4 calculation indicates a constant wavelength of 270 centimeters, since the voltages are constant. The increased heating current, however, means greater electron emission and greater space charge. For this reason the "electron-dance" is accelerated, and the wavelength shortened. The fact that for low heating currents, meaning negligible space charge, the wavelength is very close to the theoretical value, upholds this view.

The curves of Fig. 6 show total emission current, as the sum of plate and grid currents, plotted to grid voltage, in one case

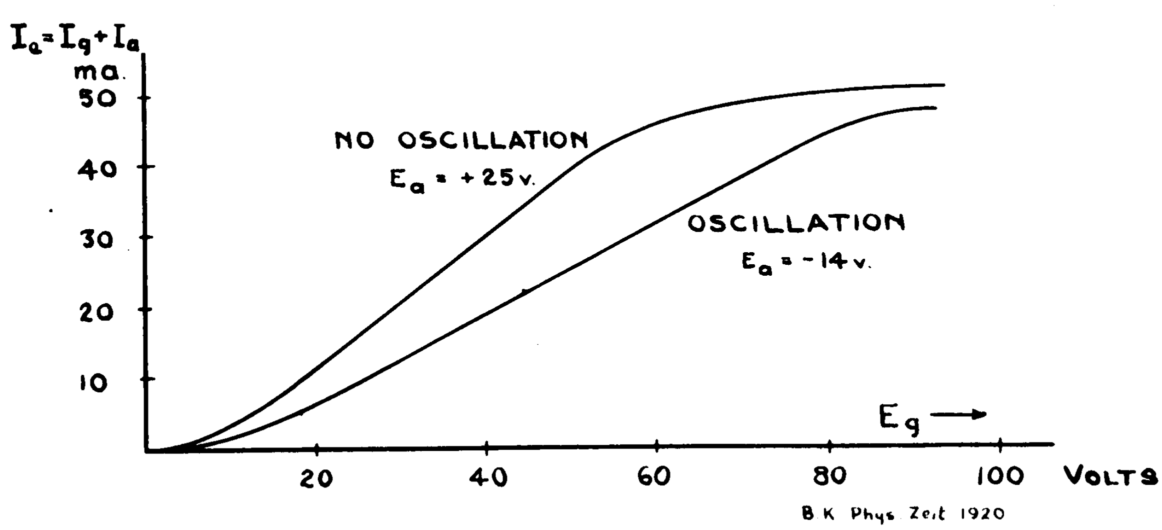


Fig. 6

where oscillations are allowed to occur, and in the other where oscillations are prevented by a positive plate voltage. Although the difference for the two curves in plate voltage is 39 volts, the amplification factor indicates that this shifts the characteristic of the tube only a very few volts. The results to be noticed are that with oscillations occurring, the saturation current is only reached with a grid voltage of 90 volts, while where there are no oscillations present, saturation occurs at 60 volts; and of greater importance, the fact that the total emission current is appreciably lower where oscillations exist. The conclusion drawn from this is that the existence of a space charge must accompany the presence of the oscillations, and the wavelength will always differ from the calculated value for this reason.

Tests made with tubes having anode diameters of 2.1, 3.1 and 3.5 centimeters indicated exactly the predicted effect of this variable on the wavelength. It was found that more intense oscillations were obtained with tubes having finer grid wire and greater pitch of grid winding, since this allows a larger proportion of the emitted electrons to pass through the grid on each phase. No oscillations of any kind could be obtained with tubes not symmetrical in construction.

"Using a tube of anode diameter 2.1 centimeters, with 500 volts on the grid and the highest reasonable heating current, we obtained a wavelength of 43 centimeters and could get no lower. It should be possible to use higher voltages, and to construct a tube with an anode diameter of the order of 0.5 centimeters; under such conditions the wavelength would have a lower limit of about 10 centimeters."

Chapter III

Gill and Morrell

It is remarkable that less than a dozen important original papers on this subject were published in the seven years following the announcement of the discovery of electron oscillations. Usually a new and broad field of research such as this, about which such a large number of conflicting opinions can exist, will provoke considerable controversy and a large amount of valuable experimenting and writing will result; but not in this case. The second paper in the literature worthy of consideration did not appear until 1922, and was not followed until 1924 by a very few more.

This second paper [9] is, however, one of the few really important ones there are, for several reasons. It brings out a fairly complete study of the characteristics of the oscillations; it discloses many features that Barkhausen and Kurz had not observed; and it sets forth the first and one of the few exisiting mathematical theories for the mechanism of the oscillations. Unfortunately the theory is based on assumptions which Gill and Morrell later admit were not justified, and it is of interest now mainly to illustrate the approach to the subject.

The greater part of the paper is devoted to purely experimental results, and because these are of considerable importance, it will be worth while to consider them in connection with the circuit used.

A single tube was used throughout, of the Marconi MT5 type, and was selected from a large number as being the most symmetrical in construction, and being sufficiently gas free that the cause of oscillations could not possibly be credited to ionized gas in the tube. This special selection with regard to symmetry was made because all calculations must be made with regard to perfect symmetry of the electrodes, and if experimental results are to be compared with theoretical figures, this symmetry must exist in the tube used. These Marconi tubes possess several desirable features. Their filament along the length of the plate and grid consists of a single straight wire, but at each support a short part of the wire is wound in spring form, and there is a slight tension present. This allows the wire to remain perfectly straight even though there may be considerable expansion on heating. The filament emission is quite high under rated conditions and is very constant at the values which were used. The plate lead is brought out of the top of the tube, while the grid lead comes out at the base, resulting in very high insulation resistance. With this arrangement, by connecting a strip of tin-foil around the center of the tube and grounding it, very minute anode currents may be measured with an electrometer.

The apparatus used is illustrated in Fig. 7. The general layout is much the same as that used by Barkhausen, but with the important difference that the Lecher wires connected to the tube have a length of 850 centimeters, plus leads to the tube terminals of about 70 centimeters length. The two condensers C and the thermo-couple T constitute the movable bridge on the wires, and the galvanometer connected to the output of the thermo-couple is considered as measuring the intensity of oscillation. The potentiometer S allows the anode potential to be varied from plus three to minus three volts with respect to the negative filament terminal.

"With this arrangement the electrons set free at the filament move outwards under the positive voltage V of the grid, and a certain number go direct to the grid and are collected there, the remainder pass through the grid and if the potential of the plate is just less than that of the filament, they return to it and are finally collected on the grid. If, on the other hand, the plate potential is a little above that of the filament, a certain proportion of those getting through the grid reach the plate. If the plate potentiometer is now adjusted until the plate current is just zero, it will be found that with the bridge in certain positions a plate current appears. It was the presence of this plate current which led Barkhausen to the discovery of the short waves. With the present apparatus these oscillations are also made apparent by the deflection of the galvanometer attached to the thermo-junction. The positions of the bridge at which the galvanometer gave a maximum deflection were fairly sharply defined and did not always coincide with the positions for maximum plate current."

If for a given tube there should be a certain optimum wavelength λ produced by a grid voltage V, by starting the bridge on the Lecher wires from a position close to the tube, and slowly moving it away from the tube along the wires, maximum currents in this external circuit would logically be expected to occur at positions of the bridge for which

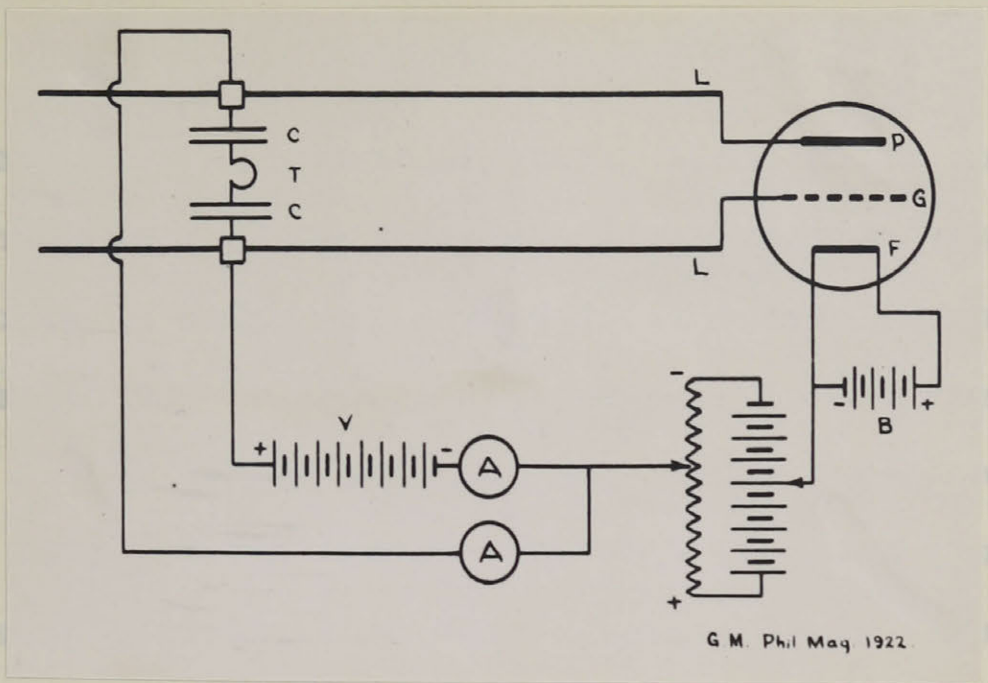


Fig. 7

the external circuit is tuned to wavelengths of integral multiples of λ . The theory of Lecher wires is such that in the perfect case the resonant wavelength is a linear function of the length, and the deviations from this caused by practical considerations are almost negligible. It would then be expected that, on moving the bridge as described, the positions for maximum current would occur at equally spaced intervals along the length of the wires, and the wavelength of the oscillations would be measureable simply as twice the distance between such positions. Gill and Morrell were the first to find that this is seldom the case.

It is found in the majority of cases that there are two or more sets of positions, forming as many series of equal spaces, and as the spacing is different in each set the indication is that the grid voltage V is able to maintain more than one wavelength of oscillation.

To be able to measure these various wavelengths separately, the obvious solution is to measure wavelength on a secondary circuit loosely coupled to the oscillator circuit, which will not affect the mode of oscillation. Under these conditions the bridge on the primary circuit may be set at any desired point to bring out any particular wavelength, and this wavelength may be accurately measured in the secondary circuit.

"A second pair of long Lecher wires were set up with a loop joining one end, and this loop was brought near the valve circuit. When the secondary is in tune with the primary the current in the primary is reduced. The deflection of the galvanometer connected to the primary circuit may be reduced by as much as 50% when the bridge in the secondary circuit is in the tuned position, and a movement of 0.5 centimeters either way will restore the primary current to its normal value. All the wavelengths quoted were measured on this form of wavemeter and may be taken as accurate to 0.5%."

The first and most important test described by Gill and Morrell is the following: It is of considerable significance as being conclusive proof of the dependence of the wavelength of electron oscillations under some conditions on the external circuit of the oscillator.

The test is made with the apparatus described above, with the condenser bridge and the thermo-couple on the Lecher system at the end away from the oscillator, so that the external circuit consists of some 900 centimeters of this system. With the filament heated to allow a few milliamperes emission, and with the plate at two volts positive, the grid voltage is raised in steps of two volts, from 16 to 120 volts. The results are shown in Fig. 8, as galvanometer deflection plotted to grid voltage.

"The curve shows that oscillations are occurring over nearly the whole range, but that the intensity has maxima for certain values of grid voltage: 16,24,42,58,82,114. The wavelengths for the corresponding ranges are 586 centimeters, 451 centimeters, 366 centimeters, 307 centimeters, 262 centimeters, 223 centimeters. These correspond to the free oscillations of the system, 920 centimeters long plus a slight correction for the leads in the tube itself.

The system of wires connected to the valve therefore presents a selection of various modes of oscillation to the valve, from which the valve chooses the ones suitable for the particular voltage V between the grid and the plate, the sharp rise just before the various maxima indicating that the system oscillates on the longer waves by preference."

It is apparent from these results that the oscillator will oscillate at constant wavelength for a considerable range

Fig. 8

where this wavelength is determined by a mode of the external circuit. To show the reversibility of this dependence, i.e. the range of wavelength which can be produced at a single grid voltage on varying the external circuit, a modification of the original circuit is used. In this case the Lecher wires are replaced by two telescoping rods, connected in the same manner as the wires. Their length can be varied from about 150 to 300 centimeters. As an example it was found that with this arrangement at a grid potential of 44 volts, an emission of 1.5 milliamperes, any wavelength from 320 to 451 centimeters could be produced, maximum intensity being observed at 323 centimeters.

The other experimental results recorded are of no importance.

In developing their mathematical theory for the oscillations, Gill and Morrell first make the following simplifying assumptions, without which the development of equations becomes extremely involved:

(1) That the grid and plate may be regarded as forming a parallel plate condenser.

(2) That all of those electrons which pass through the grid have the same velocity at the grid.

(3) That the electrons which return to the grid from the plate are nearly all collected on it.

(4) That the oscillating potential differences are small compared to the fixed potential differences.

The plate and filament are at zero potential, while the grid is at V volts positive.

Then an electron arrives at the grid with a velocity v, due to the potential V, and if it passes through to the grid-plate space and returns to the grid, it will again have velocity v. In the grid-plate space the work done by the potential V on the electrons is thus zero.

When an alternating potential $V_0 \sin pt$ exists between the grid and plate, however, the work done in this space is not necessarily zero. It may become either positive or negative. If it is negative, then the electrons are giving up energy to the oscillating system, and if this energy is supplied in sufficient quantities to overcome the losses in the system, the oscillations may be sustained purely by the motion of the electrons.

After passing the grid with velocity v, an electron becomes subjected to a retardation f, and if T is the time the electron takes to pass from the grid to the plate, then $v = fT$, assuming that the electron gets very close to the surface of the plate. Where d is the distance between the grid and the plate, the electric field due to the alternating potential is $\frac{V_0}{d} \sin pt$ and the corresponding force on an electron is $e \frac{V_0}{d} \sin pt$. The work done by this force depends on the time t_0 at which the electron passes the grid, and for a given t_0 is equal to

$$\int_0^d e \frac{V_0}{d} \sin pt \; dx$$

where the X-axis is perpendicular to the grid and plate. But the velocity at time t follows from

$$\frac{dx}{dt} = v - f(t - t_0) = f(T - t + t_0)$$

so that the work integral becomes

$$\int_{t_0}^{t_0 + T} f e \frac{V_0}{d} (T + t_0 - t) \sin pt \; dt$$

which gives, as the work done on the electron in moving from the grid to the plate

$$\frac{2\,e\,V_0}{T^2}\left\{\frac{T\cos pt_0}{p}+\frac{\sin pt_0-\sin p(T+t_0)}{p^2}\right\} \text{-----}(1)$$

By integrating from $t_0 + T$ to $t_0 + 2T$ an expression may also be found for the work on the return journey.

Obviously, the value of (1) when integrated from 0 to 2π is zero if the function is continuous throughout this range. Hence if all the electrons returned to the grid or remained at the plate, the oscillations could not exist. Where a portion of the electrons remain at the plate, however, the function becomes discontinuous, and the work integral need not be zero and may be negative.

When no work is done on an electron in the grid-plate space it just reaches the surface of the plate. If then positive work is done on it, it will remain at the plate while if negative work is done on it, it will return to the grid. Those values of t_0 which make (1) negative will be the values for which the electrons return to the grid. It is in this way found that the electrons flowing during a time π/p remain at the plate, and then the entire flow returns to the grid for an equal time.

The work done by the alternating potential on each of these two classes of electrons will be equal but will be opposite in sense and hence the net work will be zero during the grid-plate journey. It is then necessary to obtain the work integral for the return journey, for the electrons which return to the grid, and if this is negative the oscillations can theoretically be sustained.

"To find therefore if an oscillation whose periodic time is $2\pi/p$ and amplitude V_0 can be sustained by a grid voltage V, it is necessary first to find the time T which the electrons take to pass from the grid to the plate under the field due to V alone, next to find the values of t_0 for those electrons which return to the grid, and finally to find the mean value of the work integral for the plate-grid journey for these electrons. Knowing the emission current, the total work can be calculated. If this is negative and at least equal to the dissipation losses per second, the oscillation will be sustained."

Applying this reasoning to their particular apparatus, Gill and Morrell worked out the following table indicating theoretical check on the existence of the various modes of oscillation they observed experimentally.

p	Values of pt_0 for the electrons which return to the grid	Work	Wavelength
$\pi/4T$	165° to 345°	negligible	1040 cms.
$\pi/2T$	150° to 330°	-.47	520 cms.
$3\pi/4T$	135° to 315°	-.85	347 cms.
π/T	120° to 300°	-.36	260 cms.
$2\pi/T$	90° to 180°	-.32	130 cms.

Since increased emission will increase the net work input to the system, it should increase the range of wavelengths which can be maintained. This is found to be true experimentally.

Oscillations of maximum intensity are found for the value of pT approximately $3\pi/4T$. But if T varies as $\sqrt{V}$, and the wavelength varies as $1/p$, at the wavelength of maximum intensity the relation between grid voltage and wavelength will be $\lambda^2 V$ = constant, which is a decided modification of the Barkhausen Kurz concept of the universality of this relation.

"There is also a special case not explained by this theory in which the plate is very negative with respect to the filament and oscillations are produced without any current reaching the plate at all. The oscillations in this case must almost certainly be due to a velocity distribution at the grid (in contradiction to one of the simplifying assumptions here) which means that the electrons will not pass the grid in a uniform stream, and the integral of the work function need not be zero as it normally is when all the electrons return to the grid.

"The effect of the voltage drop of about 4 volts down the filament is that instead of dealing with one stream in the field due to the grid being charged to V volts there are a series of streams moving under potentials varying from V to V-4 volts. In the general case where the plate is slightly positive with respect to the filament some of the streams reach the plate, while the remainder approach it to varying distances. If oscillations commence some of these latter are periodically diverted to the plate, while in the other half-oscillations some of the former are diverted off. Thus all the streams concerned maintain the oscillations as in the simple theory."

Although the mathematics in this theory may be considerably at fault on account of the error in the simplifying assumptions, the conception of the manner in which the alternating potentials, when once set up, can maintain the oscillations automatically is the basis of almost every mechanical explanation of the oscillations ever arrived at, with the exception of those described in chapter VIII.

Although Barkhausen and Kurz made their wavelength measurements on Lecher wires directly connected to the electrodes of the tube, they presumably did not encounter the case described in this chapter in which two or more equally spaced sets of voltage nodes exist on the wires, and they therefore had no reason to suspect an influence of the external circuit on the wavelength. Certainly they made no effort to investigate such an influence, nor do they state authoritatively whether it might or might not exist, although they give the impression that they do not believe it to exist and that the wavelength depends only on voltages and tube dimensions.

The work described immediately above, on the other hand, indicates from clear experimental evidence that Gill and Morrell found the wavelength to be in one sense controlled by the external circuit, although the order of the wavelength is determined by the other factors.

These two results have given rise to the very definite distinction between "Barkhausen-Kurz oscillations" and "Gill-Morrell oscillations", the former independent of external circuit, the latter controlled by it. The two terms occur again and again throughout the literature, and the investigation of the determining causes of each has been given a great deal of space. [redacted] In the experimental work the debate on this matter will be summarized, and an attempt will be made to select the most satisfactory explanation and the one most in keeping with experiment.

According to the mathematical theory just dealt with, the possibility of oscillations occurring in a circuit such as that described depends only on the energy conditions maintaining for the electrons returning from the plate to the grid, and is not concerned with what happens in the journey from the filament to the plate. It is therefore conceivable that the electrons returning from the plate need not be the same ones that leave the filament.

The phenomenon of secondary emission in a vacuum tube allows the experimental demonstration of the possibility of generating oscillations under exactly this condition.

A.W.Hull in a paper published in the Proceedings of the I.R.E. [5] for February 1918 gave the first detailed exposition of the phenomenon, and showed it to be a state of unstable equilibrium; and that a vacuum tube oscillating in this state would necessarily oscillate at a frequency governed by the constants of a single resonant circuit in its plate lead. He did not attempt a theoretical explanation.

Horton and Davies [10], early in 1923, did further work on the subject and presented a fairly complete theory of the mechanism, but they left many experimental observations either poorly explained or entirely unaccounted for.

Later in 1923 E.W.B.Gill took up the subject [11] and produced an extremely thorough experimental study of it, as well as an hypothesis of the internal functions which would satisfactorily cover all his experimental results.

The original curves of Hull are shown in Fig. 9. They are taken for an ordinary vacuum tube, with various fixed positive potentials applied to the grid and with the plate voltage varied from zero to the particular positive value required in each case to give the desired characteristic. It is evident that for any grid voltage over 200 volts, there is a wide range of positive plate voltage which causes a negative plate current to flow. That is, electrons are leaving the plate; further, more electrons are leaving the plate than are arriving there from the filament. The only possible fundamental explanation of such a fact is that each impinging electron from the filament dislodges one or more electrons from the plate, these released electrons being then attracted to the more highly positive grid. For grid voltages below 200 volts, the same action is taking place, with the difference that the number of secondary electrons released is not as great as the number of electrons arriving from the filament, hence the plate current does not become negative.

We are not concerned here with a full theoretical discussion of the question, but a few of Gill's results and conclusions will be of interest in considering the production of electron oscillations by this action.

The circuit used by Gill is that of Fig. 10, employed a Marconi MT5 valve which has been mentioned previously. The fixed positive grid voltage is applied as shown. Where a high plate voltage is to be reached the plate voltage is varied by cell to cell changes, but for very low voltages the variation is obtained with a potentiometer. The principal curves he obtained are those of Figs. 11 and 12, those of Fig.12 being simply the detail of Fig.11 at low plate voltages.

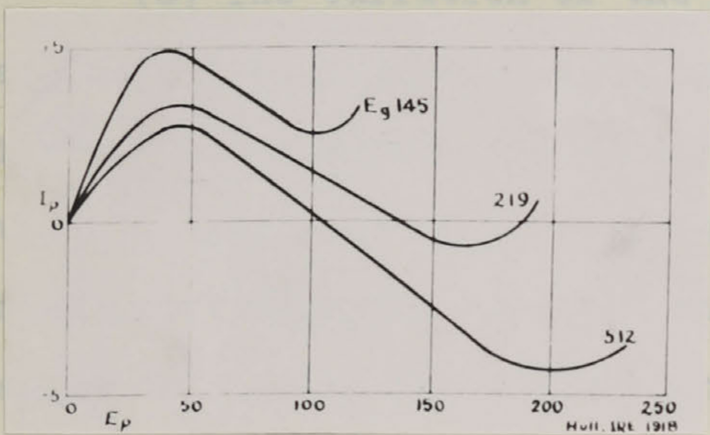


Fig. 9

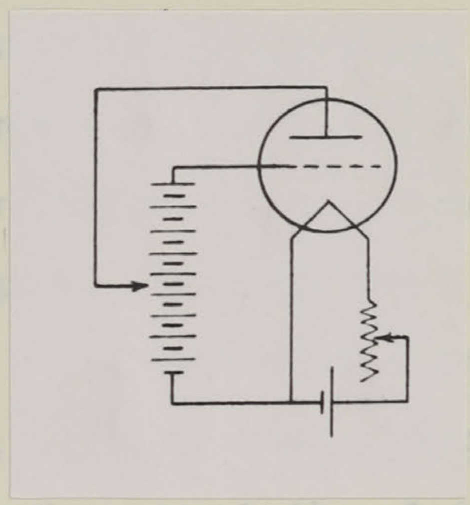


Fig. 10

The presence of secondary emission is in evidence even where the grid voltage is only 10 volts and begins to be detectable for a plate voltage of from 1 to 1.5 volts. Gill's main conclusions

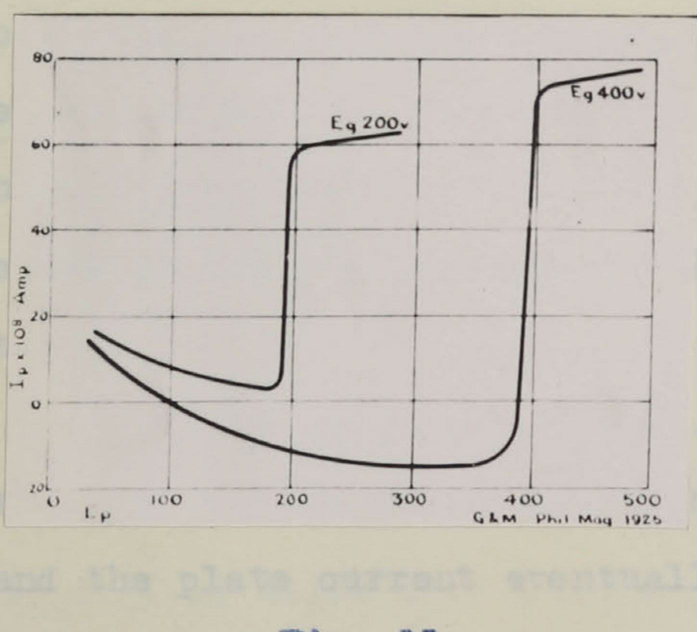


Fig. 11

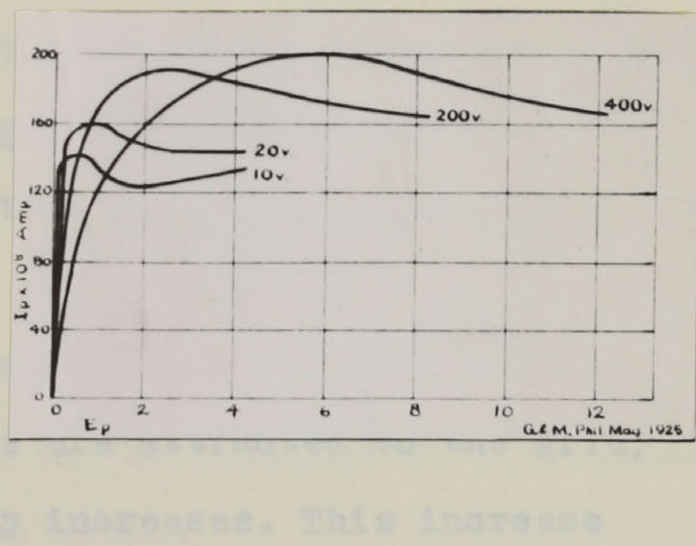


Fig. 12

from the curves are the following:

(1) The question as to whether all of the electrons receding from the plate have been dislodged from that electrode, or are merely the impinging electrons being reflected, is not important. It is obvious that in the extreme case dislodgment must take place in order that the plate current may become

negative.

(2) Some form of parasitic oscillation is very often present and may lead to erroneous results unless suppressed.

(3) The variation of the actual values of plate voltage at the critical points of the curves for different grid voltages is due to the effect of the grid voltage on the trajectory of the electron passing through the grid. Where the grid is more highly positive, the electron will be deflected at a greater angle on passing through the grid, and will trace a curve on returning to the grid which will not approach the plate as closely as would be the case for lower grid voltage. Thus a higher plate voltage will be required to pull it in. This accounts for the varying position of the first maximum point on all the curves. J.J.Thomson has shown [12] that the more obliquely an electron strikes a surface, the more secondary electrons will it release from that surface. Consequently a higher grid voltage will allow greater maximum secondary emission, but a higher plate voltage will be required to produce this.

(4) As the plate voltage approaches the grid voltage, fewer of the secondary electrons are attracted to the grid, and the plate current eventually increases. This increase occurs very rapidly where the plate voltage is almost equal to the grid voltage.

The important application of this discussion to the subject of the thesis is found under (2) above, where mention is made of the detection of parasitic oscillations which disturb the normal results of the experiment. In much the same way that

Barkhausen and Kurz were led to their discovery, Gill and Morrell set out to investigate these parisitic oscillations, and found them to be stable continuous high frequency oscillations of the same order of wavelength as those described in their paper of 1922. In fact they found them to be electron oscillations in the true sense of the word, and a paper resulted, "Short Electric Waves Obtained by the Use of Secondary Emission."

The circuit which they chose to study the properties of these waves from is the exact duplicate of that used for their first experiments, with the exception of the positive potential applied to the plate. Wavelength is measured slightly differently, in that the critical resonant points of the coupled Lecher system used for this purpose are indicated by a galvanometer in the external system itself, rather than by the effect of the external system on the current in the primary circuit. The oscillator Lechers are a pair of telescope tubes.

The only important experimental observations are as follows:

(1) Oscillations are produced only for grid and plate voltage relations corresponding to the portions of the curves of Fig. 11 which have a negative slope.

(2) Oscillations are produced where (1) is satisfied, only for certain values of the primary Lecher circuit length. For fixed voltages oscillations are sustained over an appreciable band of wavelengths according to the length of this circuit.

(3) Regardless of the actual values of plate and grid

voltage, as long as condition (1) is satisfied, the wavelength is dependent solely on the difference between these two voltages, according to the equation $\lambda^2(E_g - E_p)$ = constant, which is a logical modification of the Barkhausen equation.

This tends to confirm the original suggestion that only the electrons returning from the plate to the grid are responsible for the maintenance of the oscillations.

Gill and Morrell then go on to develop a mathematical theory for these oscillations in many ways similar to their first theory, and in fact equally applicable to the oscillations produced at zero plate voltage. Probably by coincidence their equations very closely resemble those of Sahanek [13] which will be considered in the next chapter, and which were published only a few weeks later. The numerical agreement between the results of the two is exact.

"It may be assumed that the alternating potential between the grid and plate is $V_0 \sin pt$, of periodic time $2\pi/p$. The filament is joined to potential nodes on the Lecher wire system, and, its potential being taken as zero, the total plate potential at time t is $V_p + \frac{1}{2} V_0 \sin pt$, and the total grid potential is $V_g - \frac{1}{2} V_0 \sin pt$, where V_p and V_g are the fixed potentials. The following simplifying assumptions are necessary:

(a) V_0 is so small compared with V_g and V_p that the time the electrons take to move between the electrodes is determined only by V_p and V_g, not by V_0.

(b) The plate and grid will be regarded not as concentric cylinders, but as parallel planes a distance d apart.

(c) The secondary electrons will be supposed to leave the plate with zero velocity and to move direct from the plate to the grid, and none to pass through the grid.

(d) The effect of the space charges will be neglected."

The work done per second on the electrons going from the filament to either the plate or the grid can be shown to be exactly zero, and if oscillations are to be sustained, the cause must lie in the energy conditions governing only the electrons returning from the plate to the grid.

From the formula for the velocity of the electrons the time T they take to pass from the plate to the grid, assumed the same for all electrons, is given by $d\sqrt{\frac{2m}{e(V_g - V_p)}}$.
It follows that the velocity acquired in time t by an electron leaving the plate at time t_o is

$$\frac{dx}{dt} = f(t - t_o)$$

where f is the acceleration function $\frac{e}{m}\frac{V_g - V_p}{d}$, the axis of X normal to the plate.

"The work done by the alternating potential as the electron moves from the plate to the grid is

$$- e \frac{V_o}{d} \int_{t_o}^{t_o + T} \sin pt \, dx$$

which on substitution for dx integrates to

$$- \frac{f e V_o}{d} \left\{ \frac{\sin p(t_o + T)}{p^2} - \sin pt_o - \frac{T \cos p(t_o + T)}{p} \right\} \text{ ---- } (2)$$

If the electrons left the plate in a uniform stream, the average value of (17), t_o as the variable having values from 0 to $2\pi/p$, would be zero."

However, because of the alternating potential, the stream is not uniform. Since the number of secondary electrons emitted is approximately proportional to the potential through which the incident electron has fallen, the number of secondaries given off between time t_0 and $t_0 + dt_0$ is

$$(V_p + \tfrac{1}{2} V_0 \sin pt_0)\, dt_0 \qquad \text{-----------}(3)$$

"The work done per cycle by the alternating potential on the secondary electrons is therefore proportional to the integral between $t_0 = 0$ and $t_0 = 2\pi/p$ of the product of expressions (2) and (3).

Omitting certain constants this is proportional to

$$-\frac{1}{p^3}(\cos pT - pT \sin pT - 1)$$

or the work per second is proportional to

$$-\frac{1}{p^2}(\cos pT + pT \sin pT - 1)$$

Hence if T_0 is the time of one oscillation, $T_0 = 2\pi/p$, and the work is proportional to

$$-T_0^2\left(\cos 2\pi\frac{T}{T_0} + 2\pi\frac{T}{T_0}\sin 2\pi\frac{T}{T_0} - 1\right)$$

and oscillations will be maintained if this expression is positive, and the energy is equal to that lost by radiation and resistance."

By keeping V_g and V_p constant, T is a constant, and the values of T_0 for which the above expression is positive can be worked out. The following table gives a few of the values worked out.

The range for values of the ratio greater than 2.7 includes operation of the tube as a normal dynatron oscillator and agrees with the experimental fact that the energy of oscillation for this type of oscillator increases considerably as the frequency is reduced.

T_0/T	Value of function	T_0/T for maximum energy	T_0/T for minimum energy
to 2.7	positive decreasing		2.7
2.7 to 1.0	negative	.....	1.0
1.0 to 0.66	positive	0.8	0.66

and so on alternately positive and negative.

The figures obviously indicate that several bands of wavelengths might be maintained by one set of voltage conditions, but Gill and Morrell were unable to observe more than one range, and little if any work has been done with this circuit since their time.

Chapter IV

1. The experimental work of Scheibe.

The fact that electron oscillations were discovered in Germany would reasonably lead to the idea that a considerable part of their development should take place there. Between the years 1924 and 1929 by far the greater part of all the available material originated in that country. With one or two exceptions, however, the work done in Germany has been purely experimental in nature, and there have not been many attempts at involved theories.

The paper of Adolf Scheibe [14], as the chronological head of this list is typical of the usual approach. The only satisfactory method of considering it is to set forth the experimental procedure and to reproduce the characteristics determined.

Throughout the thirty-five pages of Scheibe's article he refers to only one other source of information concerning electron oscillations, the original B-K paper. Evidently he carried out his experiments having only such previous knowledge as this paper gave him. He used a circuit almost identical with that used by Barkhausen and Kurz, but, and this is important, he arranged all the measuring instruments and batteries at distances of from 1 to 1.5 meters away from the tube, connected by twisted leads to the tube terminals, and no mention is made of the use of radio-frequency chokes. If it should be desirable, therefore, we might assume these leads to form an external circuit for the tube, which from the figure given for the length might have a resonant wavelength of the order of 2 meters or somewhat more.

As if profiting from the observations of Gill and Morrell, although this work is not mentioned, Scheibe used an inductively coupled Lecher system for all wavelength measurements. Coupling was accomplished by connecting short lengths of wire as antennae to the grid and plate terminals of the tube, and bringing the external Lecher system close to these antennae.

On moving a bridge along the Lechers, indications of oscillations were obtained only at scattered points, resulting in the curve of Fig. 13. This curve apparently indicates three

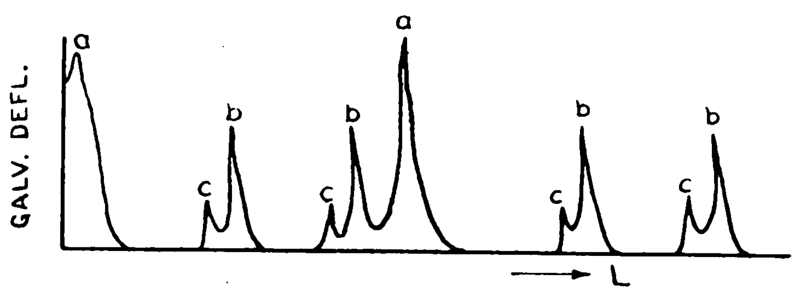


Fig. 13

modes of oscillation of the tube, although the fact that two of the sets of peaks are equally spaced can only mean that one is a reflection of the other. But there remains the fact of existence of two types of oscillation whose wavelengths are approximately but not exactly in the ratio of 2:1. Evidently the external circuit, though only coupled, does have a definite effect on the operation of the oscillator, because the two types of oscillation could not exist at the same time unless one were exactly a harmonic of the other.

Scheibe then goes on to derive the classical formula for the true wavelength of electron oscillations, taking into account the fact of cylindrical electrodes, and not assuming them plane as is usually done.

The important mathematical difference between this and the common wavelength formulae is that,since the potential in a cylindrical space is an inverse function of the distance from theccenter,the over-all potential between two electrodes in a tube will be the integral of this inverse function between the radii of the two electrodes,which becomes the natural logarithm of the ratio of the two radii.

The resulting expression is the same as that for plane electrodes,multiplied by the sum of two factors,one involving the ratio of grid radius to filament radius,the other the ratio of plate radius to grid radius,while the second also corrects for the fact that the voltage in the grid-plate space is the difference of the applied grid and plate voltages. The formula is the following:

$$\lambda = c\tau = \frac{4c.r_1}{\sqrt{2\frac{e}{m}E_g.10^8}}\left\{ f\left(\sqrt{\ln\frac{r_1}{r_0}}\right) + g\left(\sqrt{\frac{E_g}{E_g - E_a}\ln\frac{r_2}{r_1}}\right)\right\} \text{ cms.}$$

where the functions f and g have the meaning

$$f(x) = x\,e^{-x^2}\int_0^x e^{u^2}du$$

$$g(x) = x\,e^{x^2}\int_0^x e^{-u^2}du$$

Scheibe gave a short table of the values of f(x) and g(x), but calculations cannot be made from them with accuracy greater than 2 significant figures.

Kapzov and Gwosdower in 1927 published [15] tables of these functions calculated at much smaller intervals,and accurate to 5 significant figures.

The argument of the function f depends on the ratio of the grid diameter to the filament diameter. The filament diameter is usually not measureable with any high degree of accuracy, but a tungsten filament requiring one ampere for heating has a diameter of the order of .005 centimeters. Consequently the ratio may be taken generally as lying between 75 and 150. The natural logarithm of the ratio is between 4.0 and 4.8 and the root of this lies between 2 and 2.2. The function f has a limiting value, with its argument infinity, of .500. Unless very extraordinary tubes are used, the value of the function may be assumed without serious error to lie between .58 and .62.

The argument of the function g is a much more exactly known quantity, and full advantage of accurate tabulations of its value can be taken. Further, it is a function which increases rapidly and continuously, and consequently we cannot assume an average value for it. It will be shown later that there is very good evidence for believing that oscillations cannot occur if the ratio of plate diameter to grid diameter is less than 2.0 or greater than 5.0. At zero plate voltage this gives the lowest possible value of the argument of g as 0.82, and the highest value as 1.20. If oscillations could occur at appraciable positive plate voltages, the argument would be higher.

The tables by Kapzov and Gwosdower for these functions are given in the appendix.

Scheibe devotes the remainder of his paper to developing experimentally all conceivable wavelength characteristics, and comparing them in every case with the characteristic given by his formula for the same conditions. We need consider these only briefly.

(1) The variation of wavelength with filament current. The single curve given is that of Fig. 14. It will be noticed that the mathematical formula for the wavelength is not a function of the emission current, and consequently this curve should theoretically be a straight line. The fact that it is not so indicates that the mechanism of the oscillations is slightly modified by the density of the electron streams in the tube, by any effect the magnitude of the heating current may have on the initial velocity, and possibly by the magnetic field surrounding the filament. The various aspects of this problem will be discussed later.

(2) The effect of grid and anode voltages on the wavelength. In this respect Scheibe has obtained results which have never been exactly duplicated. He has been able to get continuous curves of decreasing wavelength for increasing negative anode voltages up to several hundred volts. A typical curve is that of Fig. 15, which shows the anode voltage characteristics for three different grid voltages, and also gives the calculated characteristics for the conditions existing. The characteristic given by the Barkhausen wavelength formula for the highest grid voltage is shown, and shows up the superiority of the formula which considers the cylindrical shape of the electrodes.

For zero anode voltage the Barkhausen formula indicates wavelength to be dependent on only one dimension, the plate diameter. The ratio of plate diameter to grid diameter is not involved.

The Scheibe formula gives decidedly different calculations for tubes of the same anode diameter but different grid diameters. The function f(x) is substantially constant so that the wavelength varies as the root of the grid voltage, and as some power slightly less than the first of the function g(x).

On increasing the negative plate voltage the function g(x) and the wavelength both decrease. To obtain the shortest waves, therefore, the highest possible negative plate voltage should be used, in conjunction with the highest positive grid voltage. At the same time the grid diameter should be a minimum and the ratio of plate to grid diameter should be a minimum.

Scheibe shows that he obtained oscillations with tubes whose ratio of plate to grid diameter varied from 5.81 to 2.14. In referring at another point to the tube whose ratio is 5.81, however, he gives its plate diameter as 1.72 centimeters and its grid cross-section as a square of side 0.6 centimeters. It would appear from this that the ratio should be about one-half the stated figure.

Fig. 13 indicated that at any one grid voltage two types of oscillation could exist, depending on the position of the bridge in the couple circuit. On experiment Scheibe found the ratio of the wavelengths for these two types to be very close to 2, except in the case of one tube whose electrodes were eccentircally placed. By curves such as those of Fig. 16, where the variable d is the length in centimeters of an external Lecher circuit connected directly to the electrodes of the tube, he proves the existence of a definite influence of the external circuit on the wavelength for maximum intensity

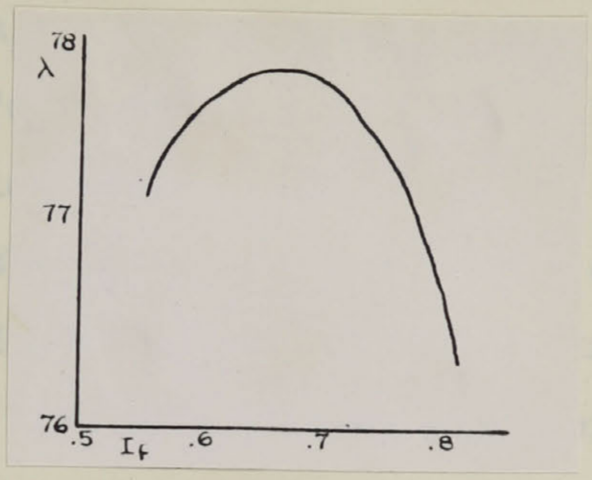


Fig. 14

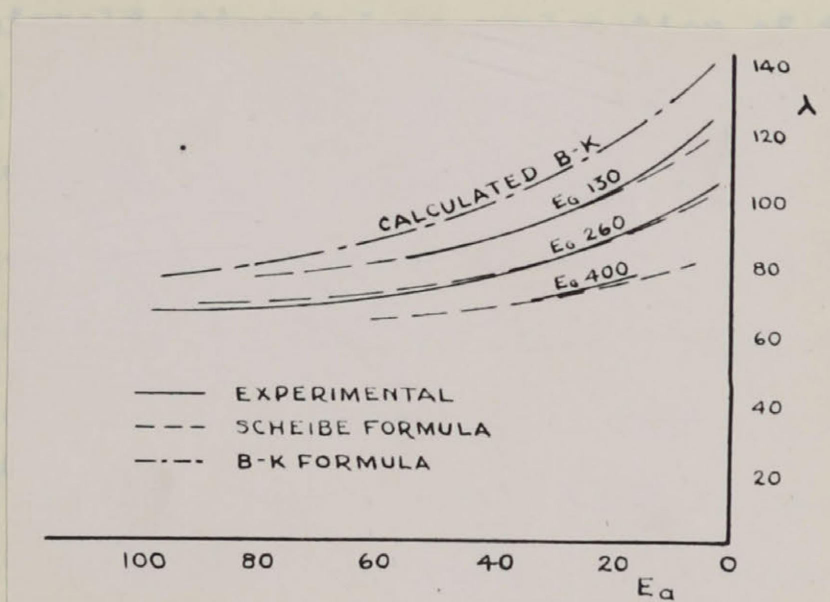


Fig. 15

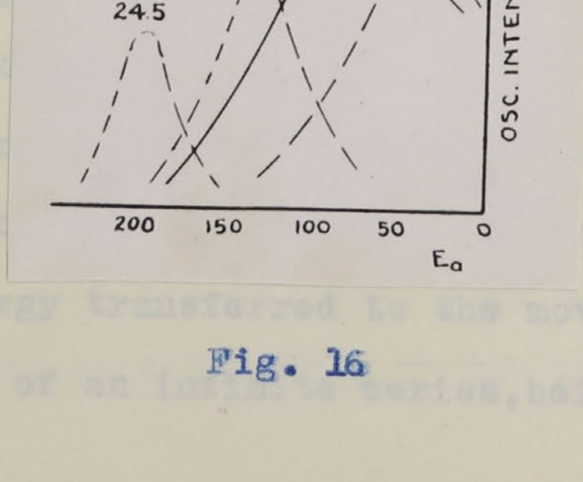


Fig. 16

of oscillation, and on the value of this maximum.

Scheibe's important contribution is, without doubt, his wavelength calculation formula. Almost the whole of the remainder of the paper consists simply of an elementary experimental demonstration of the validity of the formula. Why he should have been able to get oscillations continuously for such a wide range of anode voltage is a question which at present it is difficult to answer. Some feature of the construction of the tubes is probably the explanation. Scheibe himself attempted no explanation of the conditions governing oscillation or non-oscillation for the circuit.

2. The theory of Josef Sahanek.

Appearing within a few weeks of the time of the second paper of Gill and Morrell, and closely parallel to it in subject, although differing in mathematical approach, is the paper of Sahanek [16] which advances a theory of the oscillations produced through secondary emission, and takes into consideration the cylindrical shape of the electrodes. The conclusions to be derived from the theory are supposed to be equally applicable to the generation of oscillations by any other "electron" method, where the electronic motion is self-sustaining.

Too much space would be required to present the entire theory, and no particular object would be served. The general effect is as follows:

Expressions are derived for the various energy sources and losses throughout the system. A final expression is arrived at for the energy transferred to the moving electrons, which is in the form of an infinite series, being the following for time dt:

$$dE = \left\{ \frac{i_a}{V_t} E_0^2 \left[1 + \frac{4}{\ln \frac{\rho_A}{\rho_G}} \left(\mathfrak{A} \cos \frac{2\pi}{\tau} \vartheta + \frac{2\pi}{\tau} \vartheta \mathcal{B} \sin \frac{2\pi \vartheta}{\tau} + \right) \right] \sin^2 \frac{2\pi}{\tau} t \right\} dt$$

where i_a is the anode current

E_0 is the energy supplied by the plate and grid batteries

V_t is the filament potential

ρ_A and ρ_G are the anode and grid radii

ϑ is the resonant period of the external circuit

τ is the period of the oscillations

$\mathfrak{A}$ and $\mathcal{B}$ are constants formed from series

Oscillations are possible if the integral of the above expression throughout a cycle is negative; i.e. if

$$\int_0^\tau dE < 0$$

If the infinite series in the energy expression be represented by θ, the energy requirement for oscillation can be changed to the requirement

$$\theta < -\tfrac{1}{4} \ln \frac{\rho_A}{\rho_G}$$

θ can be calculated for various values of ϑ, and ρ_A/ρ_G. If then the corresponding values of $\frac{1}{4} \ln \rho_A/\rho_G$ are known, the existence of oscillations for different conditions can be determined. Fig. 17 illustrates the complete results of the whole theory for particular chosen values of the potentials, for values of the radius ratio from 1 to 5, and for values of the resonant period of the external circuit up to 4 times the period of the oscillations.

These curves account very exactly for the experimental observation of Gill and Morrell. They show firstly that oscillations are possible only if the ratio of plate to grid diameter lies somewhere between 2.0 and 5.0, both of these figures being fairly exact, although not integral. A maximum oscillation intensity is indicated for some particular period of the external circuit, and it is also clear that if the resonant period be varied too far on either side of this optimum value, oscillations will cease.

When θ is known, an expression for the actual oscillation energy in the system can be worked out, which takes into account every conceivable factor including emission current, applied potentials, radii ratios, and external circuit period. This expression is given as

$$\eta = \frac{-i_a}{\ln \rho_A/\rho_G} \cdot \frac{E_0^2}{V_t}\left(\frac{1}{4}\ln\frac{\rho_A}{\rho_G} + \theta\right)$$

If the grid is eccentric on the anode, the development of the theory indicates that oscillations will only be possible up to a certain limit. An integration of energy over elemental radial strips from the center of the grid allows this determination.

Eccentricity of the filament has no theoretical effect on the operation of the oscillating mechanism.

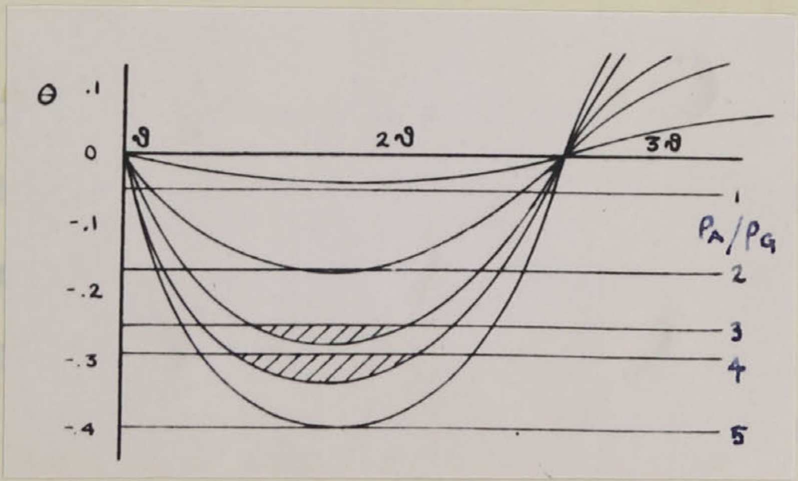


Fig. 17

3. The multi-tube circuits of Grechowa.

The remaining papers of this chapter are purely experimental in nature, but are important in that they advance for the first time the idea of using two and more tubes in a circuit generating electron oscillations.

Grechowa begins his work using the circuit of Fig. 18, with two tubes approximately similar. It will be seen that there is no direct coupling between the grid and plate circuits of the tube and there is thus available the opportunity of determining which of these circuits has the greatest control of the oscillations.

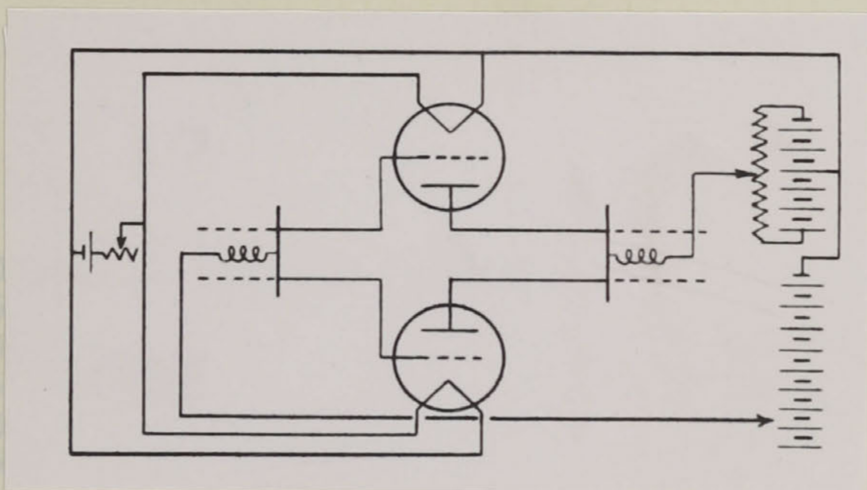


Fig. 18

Grechowa found immediately that "the voltage nodes and loops are much stronger on the plate wires." "Grounding a voltage loop on the grid wires reduced the oscillation current only 25%, while grounding a voltage loop on the plate wires reduced the oscillation current to zero."

A comparison of the resonance curves for the externally coupled Lecher system when coupled to the grid or plate circuit of the oscillator is given by Fig. 19, and confirms this same observation. Resonance is much sharper when coupling is with the plate circuit.

In agreement with the indications of the above two effects it is further found that the wavelength is governed more

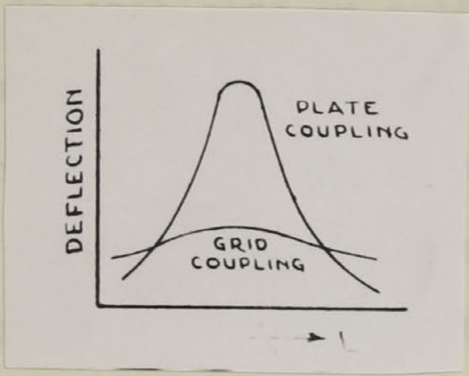


Fig. 19

definitely by the dimensions of the plate circuit than by those of the grid circuit. The results which lead to this conclusion are given tabularly as follows:

Table I

E_a = 0 E_g = 110

A	G	Wavelength
40 cms	21 cms	72.0 cms
35 "	21 "	69.6 "
30 "	21 "	67.2 "
25 "	21 "	64.5 "
20 "	21 "	62.6 "
15 "	21 "	60.5 "

Table II

E_a = 0 E_g = 110

A	G	Wavelength
40 cms	31 cms	72.1 cms
35 "	31 "	69.8 "
30 "	31 "	67.2 "
25 "	31 "	64.6 "
20 "	31 "	62.2 "

Table III

E_a = 0 E_g = 110

A	G	Wavelength
30 cms	10 cms	67.2 cms
30 "	15 "	67.2 "
30 "	20 "	67.2 "
30 "	25 "	67.2 "
30 "	30 "	67.2 "
30 "	35 "	67.2 "
30 "	40 "	67.2 "
30 "	45 "	67.2 "

Table IV

E_a = 0 E_g = 110

A	G	Wavelength
20 cms	10 cms	62.7 cms
20 "	15 "	62.7 "
20 "	20 "	62.7 "
20 "	25 "	62.7 "
20 "	30 "	62.7 "
20 "	35 "	62.7 "
20 "	40 "	62.7 "
20 "	45 "	62.7 "

Tables I and II indicate the very considerable effect on the wavelength of the dimensions of the anode circuit, while tables III and IV show that to the degree of accuracy obtainable with the apparatus, the wavelength is independent of the length of the grid circuit. It is found, however, that throughout tables I and II the intensity of oscillation as given by the plate current is approximately constant, while the length of the grid circuit has a marked effect on this quantity. There is in each case an optimum length of grid circuit, which would appear to be approximately equal to the plate circuit length, or at least to vary directly with that length.

Grechowa also found that oscillations were not continuous throughout the safe grid voltage range, and gives curves of the type of Fig. 20 that illustrate this. Wavelength variation to correspond with this curve is not given, but it would seem probable that it should correspond to the results expressed by Gill and Morrell for Fig.8 on page 26.

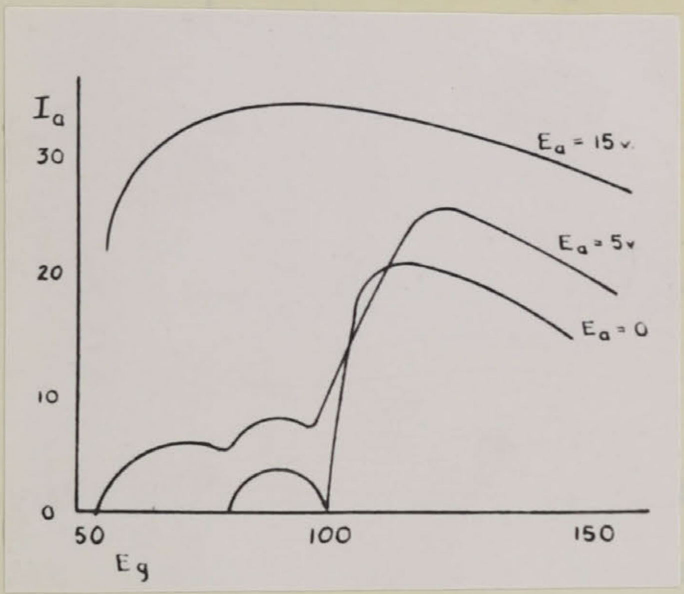


Fig. 20

In a second paper Grechowa switches his attention to the circuit of Fig. 21, which is actually the Gill Morrell with a second tube taking the place of the bridge on the Lechers. The curves of plate current to grid voltage he obtains are exactly similar to Fig. 8 of Gill and Morrell as would be expected, the only variation being changes in number, position and magnitude of peaks according to the length of the circuit A_1A_2. Gill and Morrell stated the wavelength as remaining perfectly constant across one of the oscillation

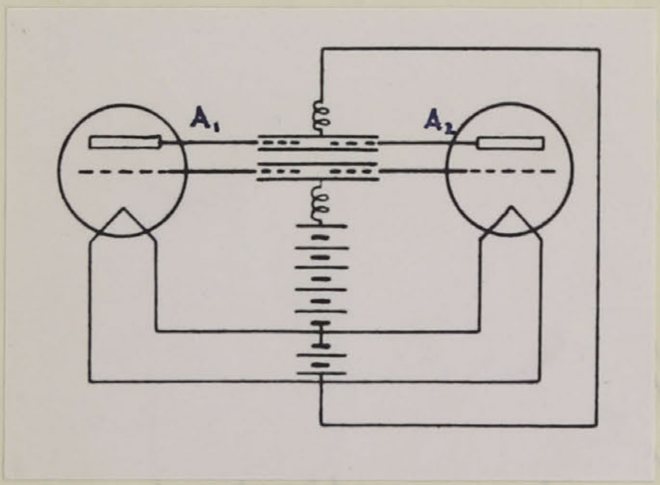


Fig. 21

peaks, probably because their equipment did not permit of greater accuracy. Grechowa finds the wavelength curve for a typical length of A_1A_2 to be that of Fig. 22, which shows a slight tendency for the higher grid voltages to decrease the wavelength in spite of the controlling effect of the external circuit. It may be noticed that an approximate curve drawn through the center points of the various partial wavelength curves takes on the form of a characteristic such as would be given by the B-K or Scheibe wavelength formulas.

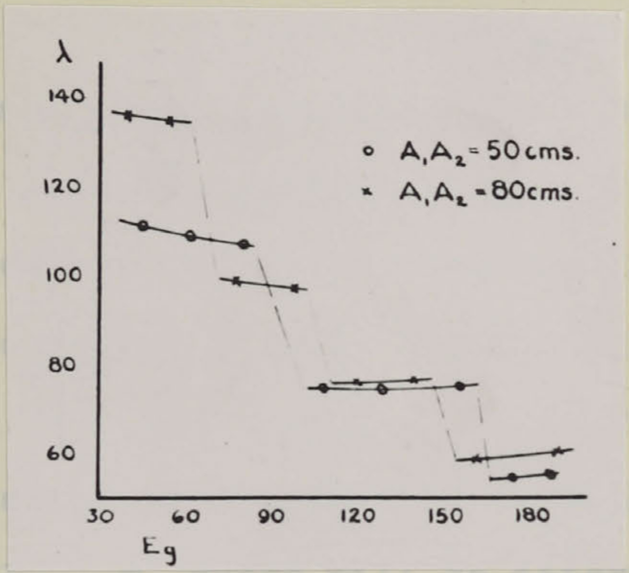


Fig. 22

It is apparent that the circuit of Fig. 21 might be extended to include any number of tubes, simply by connecting grids and plates in parallel, with circuits of suitable length between consecutive tubes. Grechowa did the first work on such a connection, using up to 7 tubes. The curve of Fig. 23 indicates the nature of the effect of using more than two tubes, and proves definitely that the addition of each tube contributes some increase to the oscillation intensity although the additional increase per tube falls off as the

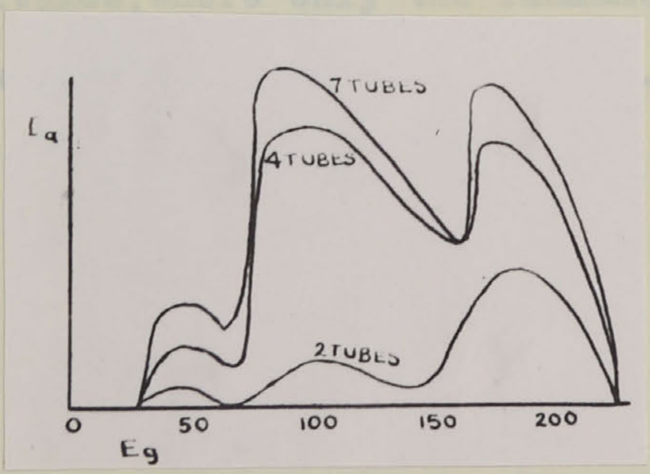


Fig. 23

number of tubes increases.

Grechowa concludes with the following generalizations, most of which are repetitions of Gill and Morrell, and none of which is in the least controversial:

(1) There is no limit to the increase in oscillation intensity on increasing the number of tubes used.

(2) The maximum intensity of oscillation and the wavelength are determined by the resonant frequency and the harmonics of the external circuit and the tube capacity.

(3) By varying the grid voltage, different harmonics in the external system will be picked out and the maxima in the I_a - E_g curve will be determined.

(4) At high grid voltages, oscillations and plate current cease. This upper limit varies with different tubes.

(5) On varying the grid voltage, the wavelength at maximum oscillation intensity does not fully agree with the formula of Scheibe as applied to a single wave-band. But the agreement is apparent if the various harmonics are considered in their relation to the fundamental. Thus at low grid voltages, where only the fundamental wave is generated, the results agree with Scheibe.

Chapter V

Experimenters in France

During the years 1927 and 1928, immediately following the work of Scheibe and Grechowa, is that of Pierret in France. His work, together with that of Beauvais, with whom he did some work in conjunction, constitutes the only important bibliography during these twp years.

"On Barkhausen oscillations obtainable with French tubes", as the title of his first article, describes its contents fully. He has simply tested the French Fotos and TMC tubes in the two-tube circuits originated by Grechowa. He has regarded plate current as a measure of the intensity of oscillations throughout, and his main results consist of curves of plate current plotted to plate circuit Lecher length as the Lecher length is decreased. These curves are of the type of Fig. 24, the recurring discontinuities indicating points of unstable oscillation.

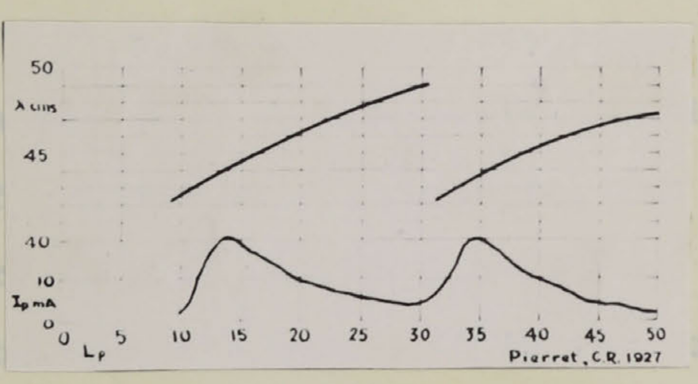


Fig. 24

On varying the plate and grid voltages suitably he is able to obtain a continuous range of oscillation from 30 centimeters to 150 centimeters; for any grid voltage there is an optimum plate voltage, and vice-versa. Although he comments on it only briefly, it is apparent that the external circuit controlled the wavelength throughout, and the Barkhausen wavelength equation did not apply. He tabulates five observation relative to the operation of the two-tube oscillator, which are not fully agreed to by later experimenters. These are:

(1) Tubes of the same dimensions and make, used under identical conditions, do not oscillate with the same ease.

(2) With two tubes in parallel, it is possible that one of them, more suited to the conditions, governs the oscillations. The other is controlled by forced oscillations. Its filament current may be reduced, or the tube may be removed entirely, or may be replaced by a small condenser, without the generated wavelength varying appreciably. The power available with two twbes is, however, much greater than that obtainable with one tube.

(3) If two tubes are such that alone they give oscillating currents of the same intensity but of slightly different frequencies under the same conditions, when coupled will oscillate on a frequency higher than either of their individual frequencies.

(4) With one of the tubes used, waves of 18 centimeters in length were obtained, which did not correspond to the harmonics of a fundamental. On moving the plate circuit bridge, the presence of oscillations at two wavelengths was observed. Consequently, according to the conditions imposed by the external circuit, one or the other of the tubes determines the frequency of oscillation.

(5) Some tubes did not oscillate until a certain filament temperature was reached. Cooling caused the oscillations to disappear. This phenomenon can be explained by the influence of positive ions, showing traces of gas liberated by the red-hot grid.

In his second paper [20] Pierret introduces some entirely new and important results. Using a two-tube oscillator as before, but with the plates of the tubes connected directly instead of through a Lecher system, with 280 volts on the grid and the plate forty volts negative with respect to the filament, strong stable oscillations were observed on a wavelength of 14 centimeters. The wavelength appeared independent of the Lecher length. The plate current is of course zero.

The application of Scheibe 's wavelength formula indicates a theoretical value of 58 centimeters in a case where the observed value is 16 centimeters. When the plate voltage is brought up to that of the filament, plate current flows again, and the normal oscillations are observed at 45 centimeters. It is found to be impossible to pass continuously from the normal waves to the shorter waves on increase of negative plate voltage. Oscillations die out at a certain point before the shorter waves appear at -40 volts.

Pierret points out that these shorter waves are probably of the same nature as some which Scheibe observed occasionally and unstably. He says:

"This new system of oscillation seems to correspond to an electron oscillation of a much higher frequency and of a small amplitude around the grid. The oscillations are maintained by the influence of the grid of one tube on the grid of the other, across the lead joining them. This lead should have such a length that the difference of phase in the oscillations on the two grids is such as tends to prevent equilibrium from being established. Periodic variations in the potential of the grid are thus produced. Because the path of the electrons is confined closely to the grid, the potential of the plate is not affected."

Finally, it is found possible, when the oscillations are started, to disconnect the plate from the battery entirely. This would indicate that their potential of -40 volts is the potential they would take up in a state of equilibrium as free electrodes.

Pierret prefaces his third paper with the statement that the good operation of the two-tube oscillators he has been accustomed to use depends very critically on how closely the tubes used are matched, and since it is difficult to get two tubes well matched, he has attempted to construct a single-tube oscillator that will give the same wavelength characteristics.

The oscillator consists solely of a copper rod connected to the grid of the tube. The outer end of the rod may be free, or may be welded to the center of a copper disc whose diameter should be equal to the semi-wavelength of the oscillations to be obtained. In the first case, the grid voltage supply is to be connected at a point distant one quarter-wavelength from the end of the rod. In the second it is connected to the disc. The plate is connected directly to a supply at 40 volts negative to the filament, while the grid is at 300 volts positive. In this circuit the TMC tube gives oscillations at 16.5 centimeters along the rod connected to the grid.

He then develops a theory for the mechanism of the shorter waves as follows:

At the center of the space between two wires of the grid there is a point of zero force. If an electron is displaced normally from the grid by a short length x from this point, a force of attraction from these two wires, which is the larger part of the total attraction, tends to bring the electron back to the point of zero force. If the grid wires are separated by a distance 2a, the magnitude of this force is $\frac{4\,qex}{a^2 + x^2}$ where q is the charge per unit length of the grid wire, and e is the charge on the electron. For high frequencies x is very small compared to a, and the x^2 term may be neglected. Then this force gives to a free electron of charge e and mass m an oscillating movement whose frequency is obtained from

$$\omega = \frac{2}{a}\sqrt{q\frac{e}{m}}$$

These oscillations produce potential variations on the grid whose frequency is double this, as in the case of a pendulum under the action of a periodic vertical force. In a resonant rod connected to the grid, oscillations will then be set up of frequency

$$\omega' = \frac{4}{a}\sqrt{q\frac{e}{m}}$$

The value of the charge q per unit length of the grid for a tube having cylindrical electrodes of radii R_f, R_g, R_p, and at potentials $0, V_g, V_p$ is

$$q = \frac{A}{2\pi R_g}\left\{\frac{V_g}{\log\frac{R_g}{R_f}} + \frac{V_g - V_p}{\log\frac{R_p}{R_g}}\right\}$$

"In calculating the value of ω' for the tubes we used, we found the corresponding wavelength to be 11.7 centimeters. One can only expect to get the right order of magnitude, because only two of the grid wires are being considered, and these are assumed in a plane. The wavelength thus depends not only on the dimensions and potentials of the electrodes, but also on the spacing of the grid wires, and the oscillator gives a frequency double that of the electron oscillations, which accounts for the very short waves obtained."

In his fourth paper [22] Pierret sets out to find under what sets of circuit conditions the normal waves will be obtained, and when the shorter waves will be obtained.

His oscillator is rather unique, and, so far as can be ascertained, has never been used by any other experimenter before or since. It is to some extent a modification of the last one described.

A single TMC tube is used, with copper discs of several centimeters diameter soldered to the ends of rods at both the plate and grid terminals. The rods run in opposite directions and are not comparable to a Lecher system. The electrode potentials are applied at the ends of the rods.

"For all the tubes tried, there exist two grid voltages V_0 and V_1 which are critical. Below V_0 only the Barkhausen oscillations can be obtained. Above V_1 only the shorter waves can be obtained. Between these two either type is obtained according to the plate voltage."

With another larger type of tube, it was found possible to obtain either the normal waves or the shorter ones merely according to the tuning of the grid rod. There is an abrupt change of frequency in passing from one stage of oscillation to the other, and it is impossible to obtain the intermediate frequencies.

For the normal waves, maximum intensity of oscillation is obtained when both plate and grid rods are tuned. Oscillations are of approximately equal amplitude in the two rods. For the short waves, on the contrary, maximum intensity is obtained with the plate rod untuned, and oscillations are observed only on the grid rod.

"These facts show that for the very short waves only the tuning of the grid rod is necessary for the maintenance of the oscillations, and if the plate rod is in resonance, it acts as a coupled circuit borrowing energy from the oscillator. The results are in agreement with the theory already advanced by us that in Barkhausen oscillations the electrons oscillate between the grid and plate, whereas the very short waves are generated by an oscillation of the electrons about the grid. In the first case the frequency of the oscillations induced in the rod is the same as that of the electron oscillations. In the second case it is double."

The final paper in the series by French experimenters [23] is one which studies the problem from a different point of view. The authors, Gutton and Beauvais, comment on the fact that different experimenters with electron oscillators have obtained widely different results, and they suggest as one possible cause the degree of evacuation of the tubes used in each case. By constructing a tube continually connected with a vacuum pump, they attempt to observe the variation of oscillation conditions with gas pressure.

With the particular tube they built, they were able to obtain the same two ranges of oscillation as observed by Pierret, the normal waves for plate voltages from a few volts positive to a few volts negative, and the shorter waves for plate voltages of about 70 volts negative.

For the normal waves neither oscillation intensity nor wavelength varies appreciably with pressure from a few hundred-thousandths of a millimeter up to eight one-thousandths of a millimeter. For the shorter waves the intensity of the oscillations is a maximum for a pressure of the order of six one-thousandths of a millimeter and gradually diminishes for pressures up to a tenth of a millimeter. The wavelength of 27.6 centimeters does not vary appreciably with either variation of external circuit dimensions or of pressure.

"The first oscillating region corresponds to oscillating frequencies dependent on the resonant frequency of the circuit.

The second region gives a higher frequency independent of this, one determined only by the dimensions and potentials of the electrodes. These high frequency oscillations seem to be capable of occurring inside the tube, even in the absence of the external oscillating circuit. They require the presence of residual gas."

Chapter VI

Further Work in Germany

All of the papers considered up to now have been dealt with individually in fairly minute detail, to show how the outstanding characteristics of electron oscillations were arrived at. From 1928 on, articles have appeared in rapid succession, and naturally a large number of them are repetitions of the earlier work that has been discussed already. In the present chapter and the following one, only a very few works will be considered in any detail. The remainder will be very briefly summarized.

The years 1928 and 1929 saw the appearance of a very large amount of material from Germany, and practically none from other countries. Hollmann and Kohl, particularly, each brought out very complete summaries of all the information available on electron oscillations up to that time, and each contributed new matter.

We begin with the first "Theory of the motion of the electrons in tubes generating B-K waves" which considers the effect of the alternating potentials throughout. It is due to Kapzov [24] and is the fore-runner of the work of Potapenko. Potapenko's theory and curves will be considered in detail in the following chapter.

The general theory of Kapzov is that because of the alternating potentials on the grid and plate, electrons leaving the filament at certain parts of the cycle of the alternation will be affected by the remainder of the cycle in such a way as to cause them to reach the plate. Electrons leaving the filament during other parts of the cycle will be influenced in such a way that they return to the grid, contribute an oscillating ripple of current to the grid current, and consequently allow the maintenance of the alternating potential on the grid. Kapzov has worked out very accurately the trajectories of the electrons throughout the cycle, and has plotted these. The curve is very similar to that of Fig. 35 due to Potapenko.

The theory considers only the possibility of the maintenance of "normal" oscillations, i.e. those whose wavelength is approximately that given by Scheibe 's or Barkhausen's formula, and does not consider the influence of an external circuit.

Shortly after this Sahanek [25] produced another mathematical theory, considerably different from his first, and applying to the general production of all electron oscillations. It will be remembered that the theory of Gill and Morrell suggested (see page 41) the possibility of generating bands of wavelengths. Gill and Morrell assumed the losses in their circuit were so high that they were unable to detect other than the normal waves. Although this second theory of Sahanek appears externally different from that of Gill and Morrell, it arrives at exactly the same conclusion as to the bands of wavelengths, and the table of ratios of period of oscillation to period of external circuit has numerical values identical with those of page 41. Sahanek includes a certain amount of experimental work which indicates these "regions" of oscillation, and bear out his calculations.

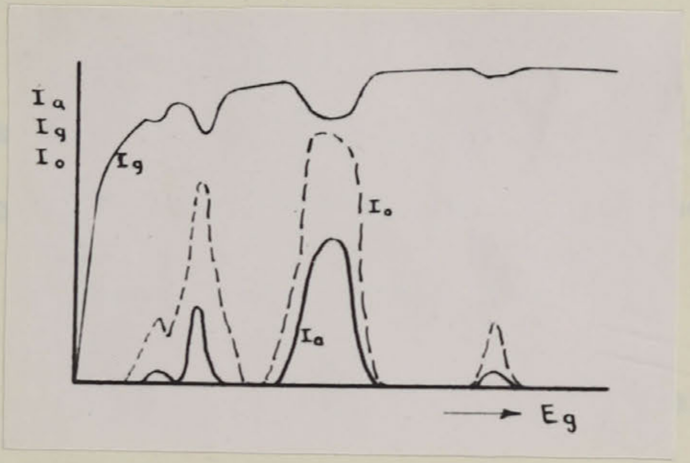
A paper by F. Tank and E. Schiltknecht [26] which has not been available in the original, gives a very good verbal expression of the implications of a theory such as that of Kapzov, as follows: "The oscillating phenomena depend on a control effect of the oscillating space-charges on the space-charge density of the emission current, which latter must therefore have reached its saturation value." It is seen over and overaagain that curves of the type of Fig. 8, obtained by 95% of all experimenters, never indicate oscillations until a fairly high degree of saturation is attained. The obvious explanation as implied by the above expression is that the alternating potential on the grid cannot exert an influence on the space-charge 'fluid' from the filament unless that 'fluid' has the property of incompressibility; i.e., unless saturation conditions exist.

The first large-scale attempt to summarize the history of electron oscillations is a paper of K.Kohl [27], which devotes 62 pages to the question, and lists a bibliography of 54 items. The important material which it includes has been dealt with here, and it introduces no worth-while experimental results. A few of the papers it considers have not been available here.

A second paper by Kohl [28] suggests the following innovation "that the effect of increased grid potential and emission current and decreased anode voltage is to shorten the wavelength, by increasing the electron density of the dielectric in the grid-anode space and thus decreasing that capacity."

A very typical article of this period is that of Kalinin, which gives a large number of curves [29] of the type of Fig. 25, illustrating the fact that oscillations do not occur until saturation current flows. The existence of saturation is very clearly indicated by the decrease in the grid current whenever plate current flows. Fig. 26 illustrates the way this should

Fig.25



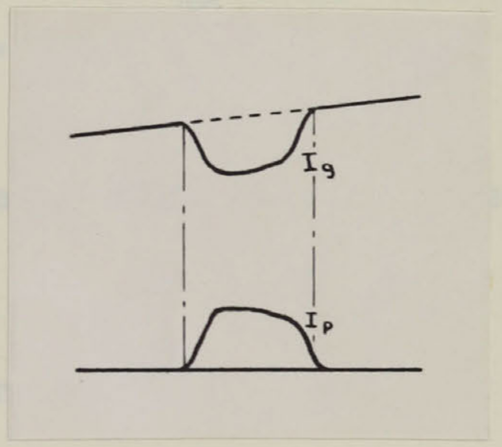


Fig.26

be expected to occur.

Kalinin observed the generalities that shorter wavelengths are only obtained for higher grid voltages, shorter external circuits, and higher emission currents. "With the plate red-hot, the grid practically melting, a filament current of 1.20 amperes and a grid voltage of 690 volts, waves of 8, 12 and 16 centimeters length were unmistakably detected, and these are probably the shortest waves that have ever been observed." Strong waves at 14.5 centimeters could be obtained under safe operating conditions.

Kalinin suggests the following relation among the grid voltages for maximum oscillation intensity in three consecutive regions of oscillation:

$$\frac{V_{n+1}}{V_n} = \frac{V_n}{V_{n-1}}$$

The relation is very well confirmed by his results.

If the various regions be considered as harmonics of the fundamental of the external circuit, and the wavelengths at maximum oscillation intensity be considered as agreeing with the Barkhausen relation, calculating the grid voltages for the various regions suggests the application of a relation of this sort in general, where the right hand side of the equation requires a constant multiplying factor of about 0.8.

A very general paper by M.J.O.Strutt [30] deals with the use of the Philips TA 0810 tube for generating electron oscillations. The curves obtained resemble very much those of Kalinin just mentioned.

The first of the many papers by H.E.Hollmann [31] is one which introduces several new features. Hollmann used four different oscillator arrangements. These vary according to the use of the Lecher system, and have the four following connections:

(1) Lechers connected to the grid and plate terminals.

(2) One rod to the plate terminal; the other, a hollow rod, is connected to one side of the filament. The other filament lead is carried inside the rod.

(3) One rod to the grid terminal; the other as in (2).

(4) A single rod with a large disc sliding along it, as used by Pierret.

In the first three cases a bridge slides along the Lechers, and distance of the bridge from the tube is the base of all the curves. The general nature of these curves is that of Fig. 27. With the arrangement (4) only the very short wavelength of 16 centimeters is obtained, for any position of the disc.

In view of some experimental work done in the present thesis, the curves of Fig. 27 warrant discussion. Two main characteristics are evidenced. For the longer waves obtained at low grid voltages, the effect of increasing the length of circuit included by the bridge is to tend to increase the wavelength up to a certain point, after which the wavelength decreases discontinuously to a certain value, and the increasing tendency is repeated.

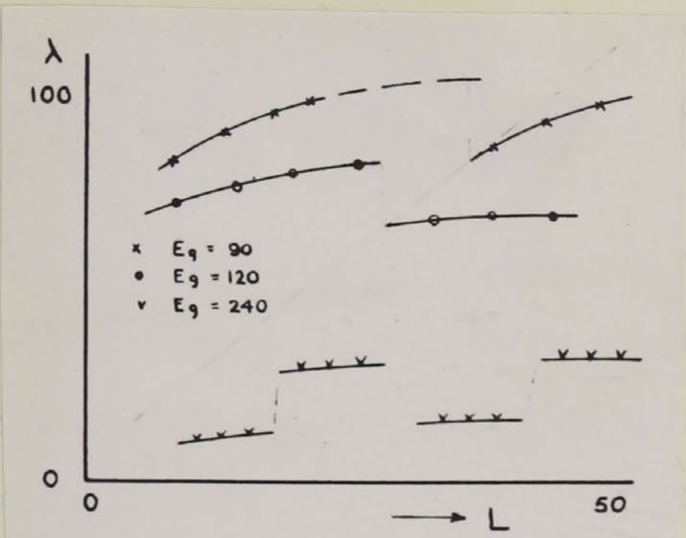


Fig. 27

It is my opinion that a curve such as this is due entirely to the characteristics of the bridge. Gill and Morrell showed that if the external system were composed of telescoping rods, so that the bridge was actaully always the end of the system for any length, the wavelength varied almost directly as the length of the system as long as oscillations existed.

The curve of Fig. 52 obtained in the present work was derived with a circuit similar to that of Gill and Morrell, but the bridge consisted of a thermo-couple sliding along the rods of the external circuit on two copper leads. It appears that the wavelength of oscillation is being governed in this case by the entire external circuit, regardless of the position of the bridge. Only when the bridge is situated at a voltage node so that its effect is annulled, does the wavelength change.

The results of Gill and Morrell and of Fig. 52 are diametrically opposite. It is probable that the curves of Hollmann represent some condition in between the two. The influence of the bridge is felt slightly, but the external circuit beyond the bridge also has some measure of effect.

Fig. 27 indicates for the very short waves at high voltages very much the same characteristics as Fig. 52 . For certain positions of the brdige the wavelength changes discontinuously to a value higher than the average. Further movement of the bridge brings the wavelength discontinuously back to its previous value.

This question is enlarged on in considering the experimental work later.

The second paper of Hollmann [32] is the only one of his available in English. His principal effort in it is to determine what distinguishes between B-K and G-M oscillations in a circuit. Using an arrangement from which curves such as that of Fig. 27 can be obtained, he takes curves of oscillation peaks along an externally coupled Lecher system for various positions of the bridge on the primary wires.

He discovers the rather surprising fact that both B-K and G-M oscillations can be generated by the same circuit, or at least such is the inference he makes from his results. Fig. 28 is a typical series of curves from which he draws this conclusion. For the bridge at position 54 centimeters, one set of peaks of wavelength 138 centimeters exists. At 55 centimeters, the wavelength of the first set of peaks has decreased to 128 centimeters, and a second set has come into existence of wavelength 98 centimeters. At 57 centimeters length of circuit, these two sets of peaks have changed to wavelengths of 116 and 101.5 centimeters respectively. At 59 centimeters length the first set of peaks disappears.

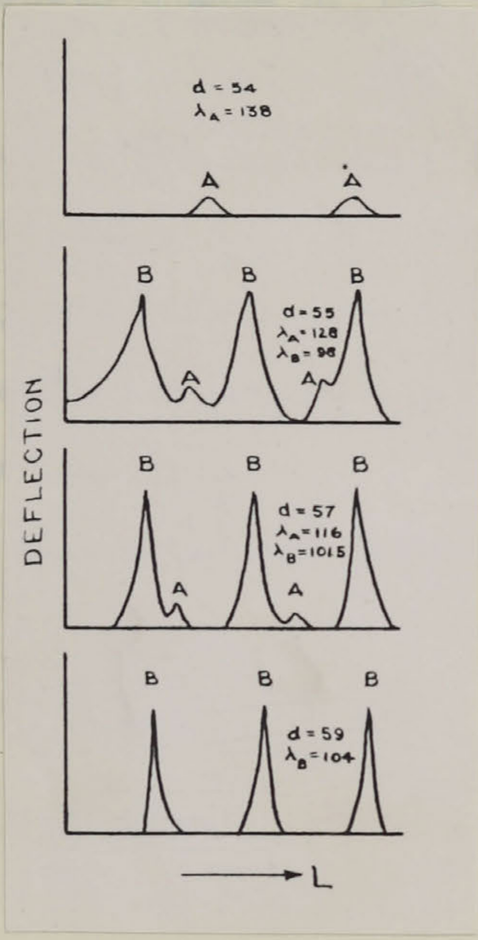


Fig. 28

Hollmann says the first set is B-K oscillations and the second is G-M oscillations. He accounts for the marked decrease in wavelength of the B-K oscillations by the rapid rise in intensity of the G-M oscillations. The very great decrease in wavelength of the "B-K" oscillations makes this theory seem somewhat unlikely. If there were no free end of the Lecher system existing beyond the bridge in each case, the explanation would be on firmer ground, but the presence of this extra system, and the fact that the bridge includes the resistance of a thermocouple, makes very possible the formation of the first set of peaks by some reflection phenomenon on the wires, and allows very considerable complication. The existence of B-K and G-M oscillations simultaneously from a circuit is hardly conceivable.

The paper sets forth a very concide wavelength formula which takes into consideration the alternating potentials on the electrodes, and is the basis of the explanation of the wavelength change of the "B-K" oscillations discussed above.

"Barkhausen and Kurz gave a wavelength formula which applied only under the simplifying conditions of constant potentials on the electrodes. If we consider an alternating field we may expect a change in the motion of the electrons, and a possible change in the frequency. The following assumptions are necessary:

(1) Anode and cathode potentials are zero.

(2) The grid is located midway between the cathode and an anode.

(3) The electrodes are plane.

(4) Space charges are disregarded.

(5) The oscillations produce an alternating potential only on the grid.

Then the electric force in the inter-electrode space is

$$E = \frac{E_g + E_0 \sin(\omega t + \phi)}{d}$$

and the equation for the motion of an electron is

$$-e \cdot \frac{E_g + E_0 \sin(\omega t + \phi)}{d} = m\frac{d^2x}{dt^2}$$

Then if the electron enters the inter-electrode space at time $t = 0$ with velocity v_0, and $x = 0$ at the same time, this expression can be integrated twice for x. To solve the resulting expression for t, two more assumptions are necessary:

(a) The frequency of the alternating field is determined by the electron frequency. Substituting $t = 0$ will give the time t required for the electrons to get back to the filament, which is half the period of the alternation, so that

(b) At time t = 0, at the instant of passage of the electron through the grid mesh, the grid receives a negative charge. At this instant therefore, E_0 has its maximum negative value, so that $\emptyset$ must have the value $-\pi/2$.

Then the duration of a semi-period is, on solving for t:

$$\tau = \frac{v_0}{\frac{e}{m.d}\left(\frac{E_g}{2} - \frac{2E_0}{\pi^2}\right)}$$

in which

$$v_0 = \sqrt{\frac{e}{m}\ 2(E_g - E_0)}$$

Substituting for v_0 and bringing in suitable constants to allow expression of potentials in volts, the wavelength is

$$\lambda = c \cdot 2 \cdot \tau$$

$$= \frac{4000\sqrt{E_g - E_0}\ d}{E_g - \frac{4E_0}{\pi^2}}$$

If $E_0 = 0$, this becomes the B-K equation.

The effect of alternating potential is quite considerable when this formula is used, but to account for the decrease in wavelength of the first set of peaks of Fig. 28 by this method would require an alternating potential of between 200 and 300 volts.

Hollmann attempts an explanation of the "shorter" and "longer" waves on a mechanism of oscillation in the grid-plate space. An electron oscillating back-and-forth between the grid and plate obviously has an oscillation frequency about one-half of that for the normal plate-cathode oscillation. The underlying principle of an electron being repelled from the positive grid during the negative half of the alternating potential cycle requires,however,necessitates the existence of a tremendously great alternating potential and the idea is not satisfactory.

A fairly good explanation of the effect of the external circuit on the oscillations and the way in which G-M oscillations are produced is developed with reference to the wavelength formula.

Suppose a circuit which is producing B-K oscillations. "Assume the external circuit tuning is changed from shorter to longer waves. At first its natural wavelength is below the excitation frequency of the B-K oscillations;hence the alternating potential between the electrodes is very small, and we have pure B-K oscillations. As the oscillation circuit is tuned to the exciting wave,the alternating potential at the electrodes rises,corresponding to the resonance curves, until a certain potential is reached.

Now the alternating field superposed on the stationary retarding fields causes a shortening of the exciting wave so that the attainment of resonance is accelerated and so on,that is,a building up process takes place which rapidly affects both the alternating potential and the frequency. The final stable state is reached when the frequency of the electron vibrations coincides with the proper frequency of the oscillating system. From this it is evident that the frequency of G-M oscillations is determined only by the natural wavelength of the tuning system."

By using specially constructed tubes,Hollmann demonstrated quite definitely that Pierret's theory of the dependence of the wavelength of the shorter waves on the pitch of the grid winding has no foundation, although the shorter waves are more easily obtained for smaller values of this quantity.

Following this last are three papers of Hollmann which attack the problem from widely different aspects. The first[33] repeats the work and conclusions of the above with regard to Pierret's theory of oscillations about the grid, but instead of explaining the "short" waves by the grid-anode oscillations mentioned above, it is found that they are due, in one case at least to a resonant circuit made up of the grid spiral and its support.

The second paper describes the effect of magnetic fields on electron oscillators. The net effect, as would be expected from the action of a magnetron tube, is that a magnetic field decreases the wavelength. The fact that this decrease also takes place for G-M oscillations leads to the statement that the whole G-M region of oscillation is displaced to a lower wavelength by the field. Very strong fields produce high frequency oscillations which can only be ascribed to the magnetron effect.

It is an obvious feature of Hollmann's work that his opinions change rapidly and radically. In a third paper, he attempts to explain all electron oscillations on a basis of negative resistance [35]. Another paper [36] deals with oscillations in grid-diodes, and indicates that an anode is not necessary for the production of electron oscillations.

Three more papers by Hollmann [37,38,39] take the form of a review of a number of other articles, and include as well most of his material used in this chapter. They introduce no new experimental or theoretical work.

Two papers by H.G.Moller are concerned with the fact that the fundamental idea of an electron oscillating around the grid cannot in general explain the mechanism of an oscillator where there is a continuous stream of electrons issuing from the filament. For an alternating current to be produced in a Lecher system under these conditions, it is necessary that the entire space charge in the tube oscillate around the grid. The resultant explanation resembles very much that of Kapzov's curve of energy integration, in that oscillation is accounted for by a "sorting-out" of electrons at the anode. This conclusion is reached in the first paper.[40] The second paper [41] suggests that the above explanation does not apply where the anode is sufficiently negative to prevent electrons from reaching it. In this case a theory of "phase-sorting" is proposed. The first electrons leaving the filament return after a certain time and produce a negative space charge which reduces the emission for a short period. This rarefaction of the space-charge travels the usual path and returns to the filament, where it creates a compression in the space charge. The oscillations can therefore maintain themselves.

This explanation of the mechanism for high negative plate voltages seems as reasonable as any that has been offered.

Chapter VII

Recent Developments

In very recent years much more attention has been given to the construction of tubes and circuits that will supply useful power at the high frequencies generated by electron oscillators than has been devoted to experimental and theoretical studies of the oscillations. There are a large number of papers listed in the bibliography at the end of the thesis that do not merit any discussion for present purposes. The opinions of the authors would appear to be that the subject is gradually passing out of the stage of experimental physics, and is capable of being applied to practical communication problems. There are only four experimental and theoretical approaches that need be considered in this chapter.

1. The most recent work of Gill.

Almost ten years after his original work on the subject, E.W.B.Gill has suggested a new theory of electron oscillations. For any region of oscillation, regardless of the variable producing it, or of its limits, there must naturally be a wavelength at which the oscillation intensity is a maximum. This optimum wavelength is the wavelength at which the electron oscillator per se tends to oscillate, and should therefore be the value given by wavelength calculations, and favored by energy considerations.

The B-K wavelength formula gives the period of the natural frequency of the oscillations as twice the time required for the electrons to travel from the filament to the plate under the action of the grid voltage. The relation of the actual period of the favored oscillation to this time of travel is a measure of the influence exerted on the travel by any internal or external agents, such as space charges or alternating potentials. The final results of mathematical theories are very often expressed by this ratio. The figure given on page 41 for the Gill-Morrell theory applied to secondary emission oscillations is 0.8.

Gill deals with his previous work very briefly. In it "the wavelengths were found to depend on the natural periods of the external circuits, but the fact that the oscillations rarely occurred on the fundamental wavelengths of these circuits, but on one of the other possible modes of oscillation, indicated that the regenerative action of the valve was most effective for certain wavelengths. The action of the valve when connected in this way is not the same as when connected in more ordinary circuits where the fundamental oscillation is practically always maintained by the regenerative action of the valve and the valve is equally efficient over a large range of wavelengths. Morrell and the author came to the conclusion that if V is the potential maintained between the grid and the other electrodes, oscillations would be strongest if the external circuit was tuned to a wavelength such that the product of the square of the wavelength and the voltage V was equal to a constant depending only on the dimensions of the tube. The experiments to be described show that this result is only partially true; the dimensions of the valve then used were unsuitable for showing what happens in the most general case."

The apparatus is identical with that of Fig. 7, the Lecher wires in this case being 616 centimeters in length. "The oscillatory circuit comprised the grid-plate capacity, the inductance and capacity of the Lechers and the inductance and capacity of the leads inside the valve.

The wavelength of the fundamental oscillation of this circuit was of the order of 30 meters, and among other modes were the values of 576 centimeters, 400 centimeters, 304 centimeters, and 304 centimeters....The study of the conditions necessary to produce oscillations of the above four wavelengths was sufficient to establish certain laws, and the experiments were made on these wavelengths only."

Two sets of experiments were made. The first gives a series of curves of oscillation current and wavelength to grid voltage for various filament currents. It is found that the 576 centimeter waves appear at the lowest filament current, and have a maximum intensity at 24 volts. The 400 centimeter waves occur at a higher filament current, and are maximized at 50 volts. The 304 centimeter wave is strongest at 91 volts, and the 248 centimeter wave at 157 volts.

Then it was found that even at a grid voltage of 24 volts, all four oscillation regions could be detected by increasing the filament current sufficiently. Two tables of figures result; as shown on the following page. i in each case is the grid current in milliamperes giving maximum oscillation intensity, the figures of table I having been taken with this adjustment.

Table I

V	λ	i	$\lambda^2 V$	$V^{3/2}/i$
24	5.76	0.66	799	178
50	4.00	2.11	800	167
91	3.04	5.04	841	170
157	2.48	12.5	965	154

Table II

V = 24 volts

i	λ	$\lambda^2 i$
0.66	5.76	21.8
1.30	4.00	20.8
2.06	3.04	19.2

V = 50 volts

i	λ	$\lambda^2 i$
2.25	4.00	36.0
4.0	3.04	37.2
6.4	2.48	38.6

Table I indicates that $\lambda^2 V$ is approximately constant, and that i almost obeys the three-halves power law. The poor agreement for the high voltage value is attributed to the poor vacuum of the tube.

"It appears therefore that with the tube used a grid voltage V is capable of maintaining oscillations over a range of wavelengths and not, as was supposed, on one wavelength only. The wavelength most strongly maintained depends on both V and the grid current, but the possible wavelengths are confined to a band. The long wave ends of the band obey the law $\lambda^2 V$ is a constant, and the appropriate values of i for these are proportional to $V^{3/2}$. In addition, for all waves in the band given by a definite value of V, the relation $\lambda^2 i$ is constant is obeyed.

In general therefore, for any values of i and V we must have $\frac{\lambda^2 i}{\sqrt{V}}$ is constant, which is more general than the old B-K relation which applies only to the long wave limit."

Gill says that the usual explanation of electron oscillations being maintained by 'compressions' and 'rarefactions' in the electron stream from the filament to the grid demands that this space be saturated, whereas the figures of table II taken at 24 volts on the grid prove that oscillations are occurring before saturation has set in. The remainder of the paper is devoted to the presentation of a theory which requires that the space between the grid and anode be carrying saturation current, not the grid-cathode space.

The method used and the assumptions of theory are not sufficiently important to make necessary its full development here. The final result is expressed by the relation

$$T = \frac{3}{2} d \sqrt{\frac{2m}{eV}}$$

where T is the time of passage of the electrons through the saturated region from the grid to the plate. If the grid is centered between the filament and the plate, the periodic time of resonant oscillations will be four times this. Expressed as mentioned on page 78, the ratio of the wavelength of maximum oscillation to the simple calculated passage time for the electron from filament to plate is 1.33.

In a very complete mathematical survey of "The Internal Actions of Thermionic Systems at High Frequencies", W.E.Benham touches on electron oscillations in an incidental way and works out the ratio mentioned in the last paragraph for the case where the full effect of space charge is taken into consideration as 0.82. He states the ratio given by Barkhausen and Kurz as 2,but it seems obvious from the definition of the ratio that this figure should be 1. Similarly he gives the figure which results from Sahanek's work as 1.67,where it apparently should be 0.83. In addition he says the following,which is very pointed: "In previous treatments of ultra-short wave oscillations there appears an increasing tendency to talk about space-charge, oscillating space-charge and so forth,accompanied by a complete omission of space-charge from the mathematics. That various workers have obtained results from their theories which are confirmed by experiment only shows how much may frequently be explained by theories which by common consent omit to take in some complicating feature. Another example of this is the omission of the initial velocity distribution.

The fact that emerges when space-charge is taken into account is that whenever there is a transit of electrons between a space-charge limited cathode and an anode,there is a negative resistance within the system for some value of pT. The negative resistance property may be regarded as inherent in the space-charge itself. The hypothesis that electrons actually oscillate about the grid is not essential to the explanation of the oscillations,and should be disregarded unless it can be proved that such oscillations actually do occur. The mathematical theory of Kapzov,which is based on reasonable assumptions,is very significant in this connection."

Benham therefore suggests that the term 'electron oscillations' has become a misleading one,and that one should refer to the electron's orbit rather than its oscillation. The term 'valve oscillations' should be taken as indicating the externally detected oscillations, and it should be made clear, according to his point of view, that there is no essential relation between the electron oscillations and the valve oscillations. From a purist's standpoint, there is a great deal of logic in this statement.

The only work remaining to be considered now is that of G. Potapenko, which is certainly the most extensive that has yet been published. As far back as 1929, he produced his first paper on the subject, expressing a belief in the fundamental truth of the mathematics of Kapzov, and showing how these could be extended to allow the existence of bands of oscillation.[45]

In that paper also, Potapenko first made use of space diagrams and three-dimensional models for the illustration of oscillation characteristics of circuits. All the important work of that paper has been repeated in his series of four papers in the Physical Review, and we need only consider these. In the first of these four [46], Potapenko explains the initial purpose of the experimenting. "Experimenting all seems to indicate that shorter waves are obtainable only by increasing the grid potential and reducing the tube dimensions. Also, increasing the grid voltage requires greater emission to produce oscillations. As this cannot go on indefinitely, the wavelength is limited.

Scheibe and Pierret, however, were able to obtain shorter waves without dangerous increase of grid voltage or emission current. We have set out therefore with the idea of obtaining these shorter waves in as pure a state as possible, and of finding out something about them."

The circuit that has been used throughout is that of Fig. 29. A vacuum tube and a ballast condenser C of equal

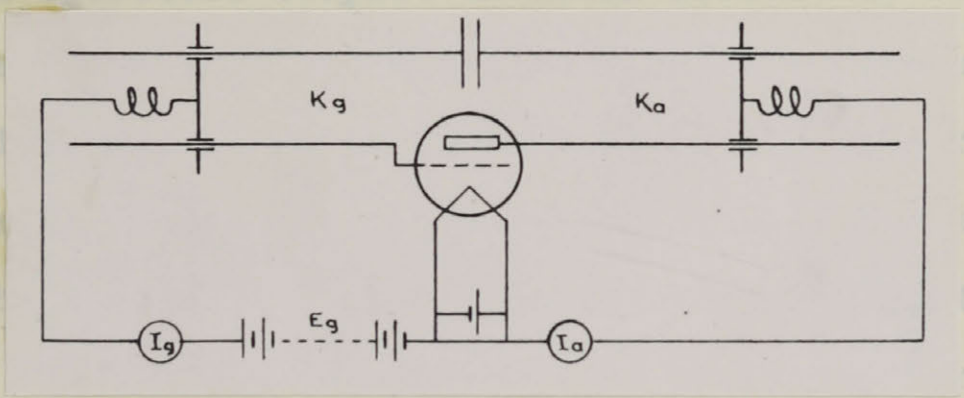


Fig. 29

capacity were placed between two oscillating circuits K_a and K_g. The circuits are copper wires, with moveable plate bridges. Each circuit had a total length of 75 centimeters. All the oscillating equipment is shielded from the rest of the circuit by chokes.

Very particular attention is called to the importance of maintaining the heating of the filament constant. At constant grid voltage this can best be checked by watching the emission current, but where the grid voltage is varied, the sum of the emission and filament currents must be kept constant. "Another important feature is the steadiness of the internal regime of the tube. Even a short over-heating, resulting in a barely observable disintegration of the filament had a very great effect on the working of the tube. It may be that observations made after the over-heating will be in no way comparable with those made previously.

A very large number of vacuum tubes have been tested. So far none of the American tubes have given any good results."

After much discussion, the use of plate current as a measure of oscillation intensity is decided as satisfactory, provided of course that the plate is at the same potential as the filament. Curves are given for the oscillation intensity in an aperiodic coupled external circuit as compared to the plate current of the oscillator, and the resemblance is sufficiently close to warrant their use. The reason for desiring to use the plate current values for this purpose is the fact of its much greater average magnitude.

It will be remembered that Grechowa, Pierret and others used two-tube oscillator circuits very similar to the one used here, with the second tube in place of the condenser C. Potapenko's objection to this is the difficulty of finding tubes with even approximately similar characteristics. Over one hundred of the Russian R5 valves were tested, and two could not be found that were satisfactorily matched.

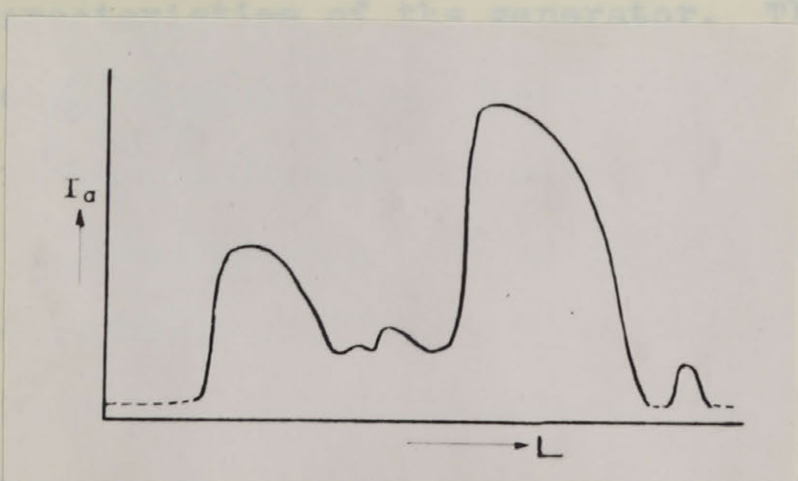


Fig. 30

It also appears to be true in general that curves of plate current to Lecher length such as Fig. 30 when taken for a two tube circuit lack much of the finer detail of those taken using a condenser at C. "Since we feel that these small points of low energy output on the curves are of particular interest, we are using a single tube circuit throughout."

Where only a capacity balance is desired, it is satisfactory to put a second tube at C, leaving its filament circuit disconnected. In this case it is important that care be taken that the sockets are of equal capacities.

The second paper of the Potapenko series [47] describes all of the experimental work upon which the series is based.

On page 83 mention is made of the used of space diagrams and models for presenting results. Potapenko has used this method almost exclusively.

"There are two schemes for the graphical representation of the work of vacuum tubes generating ultra-short waves by the B-K method. Both schemes can be used regardless of what oscillating circuit the tube is connected with or of what generator it makes a part. The first method is to represent the work of a tube or generator by means of curves showing the relation between the energy of oscillations, or the plate current and the grid potential. Such are the I_a--E_g characteristics of the generator. The dimensions of the oscillating circuits connected with the tube, their natural periods, and the heating current are kept constant.

The second scheme consists in representing the energy of oscillations or the plate current as a function of the dimensions of the external circuit. Grid voltage and heating current are kept constant. Such curves are the I_a - L characteristics, where L denotes the dimensions or the natural period of the oscillating circuit."

"As a matter of fact the energy depends on both the natural period and the potentials of the electrodes. Thus neither of the characteristics gives a complete picture of the operation of the tube. This drawback can be obviated by systematically investigating the work of a tube, varying simultaneously the potentials and the periods of the oscillating circuit. The results can be conveniently and clearly presented by what we shall call working diagrams. The use of these diagrams has a very large number of advantages and at the same time does not preclude the possibility of using individual characteristics."

A typical working diagram is that of Fig. 31, which illustrates the occurrence of the various regions of oscillation

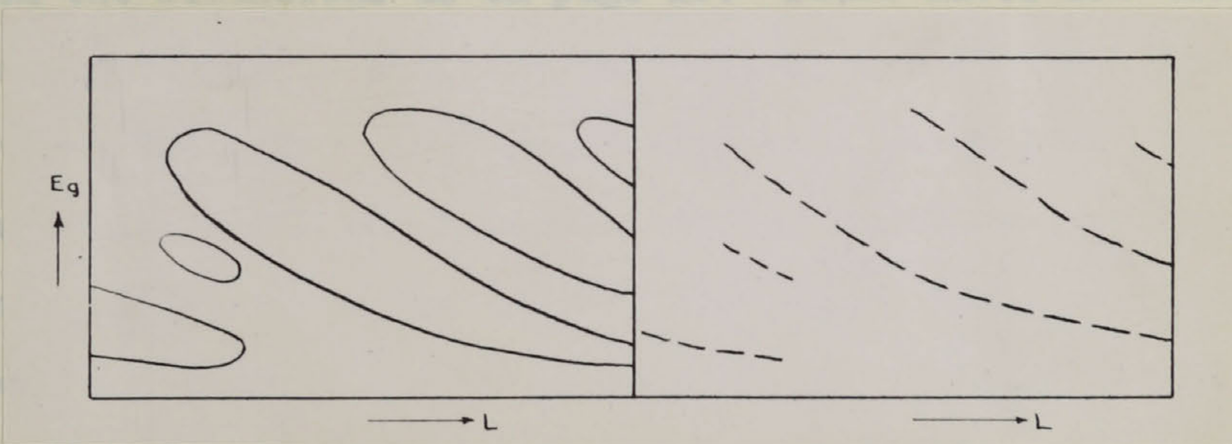


Fig. 31 Fig. 32

for all conditions of grid potential and external circuit length. Although intensity of oscillation is not represented by a dimension here, the size of an area corresponds very roughly to the amplitude of the oscillations comprising it.

A modification of this working diagram which is more useful for calculating purposes for the reasons expressed on page 78, is one of straight or curved lines which show the position of maximum oscillation intensity for each region. The distance between two such lines in two different regions at the same grid voltage is a very accurate measure of the wavelength in that region. It is found in general that the B-K wavelength relation is obeyed with a fair degree of precision where the wavelengths of maximum oscillation intensity for the various regions are considered, although the constant of the equation is different for different groups of regions. Fig. 32 is the simplified diagram.

Potapenko here makes the distinction between 'normal' and 'dwarf' waves that applies throughout his work. Normal waves are those whose wavelength is given approximately by the B-K equation, where the value of the constant is obtained from the dimensions as on page 19. Dwarf waves are those whose wavelengths are integral sub-multiples of the normal waves. The first order dwarf wave at a given grid voltage has a wavelength one-half that of the normal wave at the same grid voltage. The second order dwarf has a wavelength one-third that of the normal, and so on. Nothing higher than fourth order dwarfs have so far been detected.

Working diagrams of the type of Fig. 30 always show a number of oscillation regions of low intensity, which might very easily be overlooked in an individual characteristic curve. Potapenko finds that these low-energy regions are caused by the dwarf waves. He is thus able to realize his original desire of obtaining very short waves without the application of dangerous potentials, or the use of high emission currents.

But why are there so few dwarf wave regions? "If we take the line of maximum intensity of the dwarf waves and draw lines horizontally to distances of one-half wavelength to either side of a point in the dwarf wave region, we find we get into a region of normal waves. It would appear that if it were possible to inhibit the generation of the normal waves at these points we should get the dwarf waves." And there is a very simple means of doing exactly this.

"This may be done by keeping the anode Lecher at some constant length, and varying only the length of the plate Lecher. We can thus separate any desired wave where several are generated at the same point."

Measurements of wavelengths all over a particular working diagram revealed the presence of oscillations of five different wavelengths, in definite harmonic relation, at 72, 36, 24, 18, and 12 centimeters length. The very short waves are never found in a region by themselves, but are found on the boundaries of regions of other orders.

Thus: "A vacuum tube can generate oscillations whose frequency exceeds many times the frequency of electronic oscillations." Further, the fact that in any one region the Barkhausen relation is never obeyed, for either normal or dwarf waves leads to the conclusion that "Normal waves and all dwarf waves of all orders belong to the same type of oscillations."

It appears probable that tubes of the same type differ only in the number and magnitude of their oscillation regions, not in the fundamental plan of their working diagrams, and if a region exists it will be located at nearly the same part of all diagrams.

The reason why the dwarf waves are more easily obtained with certain tubes is due entirely to the symmetry of the electrodess The condition of symmetry is essentially a condition of equality of times of passage of the electrons in every direction in the tube. If these times are sufficiently unequal,the oscillations will be broken up. The higher the order of the dwarf waves the more they are affected by these inequalities,because the greater will be the relative difference between the period of oscillation and the times of the electrons in different directions.

Since the whole wavelength spectrum of any one tube is never fully covered,Potapenko is led to the conclusion that there are oscillating circuits in the tubes,in the electrodes or in the leads to the bases,whose natural periods are close to the periods of the observed oscillations. This conception also accounts for the observation that all dwarf waves are G-M oscillations. Nevertheless,it seems rather a weak point in the theory he has built up.

The third paper in this series is devoted to the theory which is presented to explain how the mainetance of the dwarf wave oscillations is possible.

Considered in the light of the remarks on page 78,it is apparent that first order dwarf waves are those for which the ratio of the periodic time to the time of passage of the electrons is 1/2. For the second order dwarfs,the ratio is 1/3,and so on. The formula of Gill and Morrell expressed in the equations of page 41 indicated that oscillations might be expected for several values of this ratio. The figures given would account only for the normal waves and the second and fourth order dwarfs of the present work. These two orders have not been found to be of outstanding intensity, so that the theory does not apply. In fact, there is no existing mathematical theory which accounts specifically for all these dwarf waves.

It is possible, however, to illustrate very simply a mechanism which will explain these waves. By considering

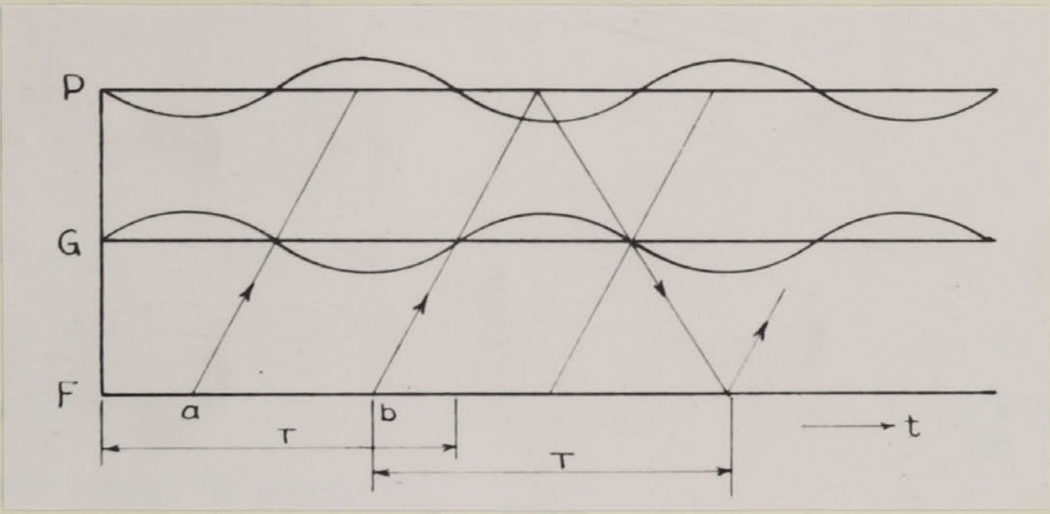


Fig. 33

electronic trajectories where alternating potentials exist on the electrodes of a tube, we can obtain a visual solution of the problem. Thus if, in Fig. 33, we plot time along the X-axis and the distance of the electrons from the filament along the Y-axis, we can determine the effect of the varying potentials on the travel. Let the alternating potentials at the grid and plate with respect to the filament be represented by two sinusoidal curves of arbitrary period. Since a constant difference of phase of 180° must exist between the oscillations of the plate and grid circuit, these two sinusoidal curves will be mirror images of each other. Because of the high grid potential, the grid will always remain positively charged. The plate, on the other hand, will be alternately positive and negative. Filament oscillating potentials can be disregarded.

Consider two electrons a and b and plot their trajectories. Assume the constant grid potential is so selected that the time the electrons take to pass from the filament to the plate is equal to the period of the alternating potentials. The electron a issues from the filament at the mement that the grid potential has its maximum value, and its acceleration to the grid will have the maximum possible value. It will pass the grid with a high velocity. On its path to the plate it is acted on by a retarding field weaker than the accelerating field that acted previously, because the grid is now less positive than before, while the plate potential is in the positive half-cycle. This electron will therefore strike the plate and give up its remaining energy.

The electron b issues from the filament when the grid potential is a minimum. It has an acceleration smaller than the particle a had, and it passes the grid with a lower velocity. In the grid-plate space the retarding field on it is stronger than the accelerating field had been. As a result the electron will not reach the plate, and will return towards the grid. As it approaches the filament on passing the grid, it again changes direction, and again leaves the filament when the grid potential is a mimimum.

Consequently, because of the presence of the alternating potentials on the electrodes, the electrons are sorted into two groups. One group is not able to produce oscillations, and gives rise to the plate current which flows when oscillations occur. "The other group will be able to oscillate, and in passing from the plate to the grid will be able to reduce the current in the tube. Thus there will be a certain order in the motion of the electrons and the current flowing through the tube will oscillate. In addition to these two groups there are the electrons that are captured by the grid before they get into the grid-plate space, and these constitute the majority, as is seen by the ratio of plate current to grid current."

It is seen then that such a mechanism will account for oscillations of the natural electron frequency. Now suppose a three-fold decrease in the natural period of the external circuit, and therefire in the period of oscillation of the potential on the electrodes. Let the grid voltage remain unchanged. From Fig. 34 it is now apparent from a study of

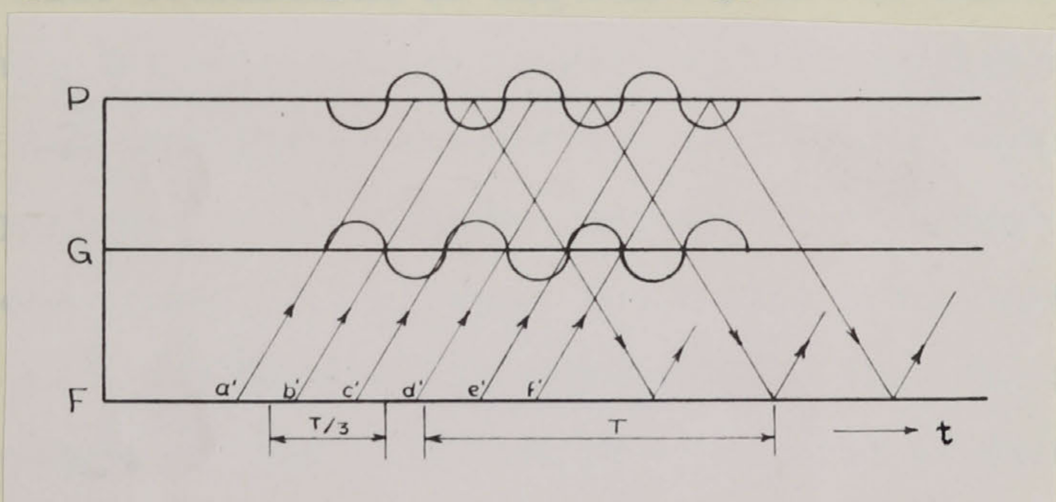


Fig. 34

the potential conditions governing the transits of the various electrons, that a', c', e' and g' will be analogous to the previous electron a and will remain at the plate. b', d', f' and h' will be able to oscillate, so that a perfectly definite order in the electron motion is again established. The current through the tube will oscillate periodically,the period of oscillation being one-third the period of the electron oscillations.

Hence "the reason why a vacuum tube can generate dwarf waves is because the tube can transmit energy into the oscillating circuit connected with it and transmit it periodically with a period equal to the natural period of the circuit,not only when this natural period is equal to the period of the electron oscillations,but also when it is any integral fraction of this time."

Even if the negative potential on the plate is so great that electrons are unable to reach it,the presence of the alternating electrode potentials causes a division of the electrons into two groups. This is the case described by Moller on page 76 as "phase-sorting".

The oscillation of the density of the current flowing through the tube and the process of transmission of energy into the oscillating circuit can be formally explained by the presence of a so-called "negative resistance" between the electrodes of the tube. The static characteristic of the tube is not a falling characteristic,so that the negative resistance in this case must be considered as essentially dynamical. The theory of Sahanek involves this idea,and it will be remembered that Hollmann suggested it (page 75).

Such,then,is the mechanism supported by Potapenko. The remainder of this paper is devoted to illustrating how the mathematical results of Kapzov bear this out, and how they can be extended to explain the dwarf waves.

Kapzov worked out,by integration with infinite series, from his energy equation involving the alternating potentials, that only those electrons emitted from the filament during a certain part of the cycle would return from the plate and contribute to the oscillations. He showed that if 0^{0} represent the start of the positive half of a cycle, those electrons emitted between -80^{0} and 60^{0} would return. But he considered only the case of alternating potentials of the same frequency as the electron oscillations. Sears [52] checked this integration by an integraph, and obtained the same numerical results.

At Potapenko's suggestion G.Kreutzer worked out similar integrals for the case of the higher frequency alternating potentials of the dwarf waves, and found quite definitely that during certain portions of the cycle in every case the electrons could return to the filament and allow oscillations to be maintained. The curve of Fig. 35 is that of Kapzov, and shows on a time base the path traced by the electron, and the velocity at the various points of its path. The curves for the higher frequency waves are identical in construction, differing only in the times for which the electrons return to the filament.

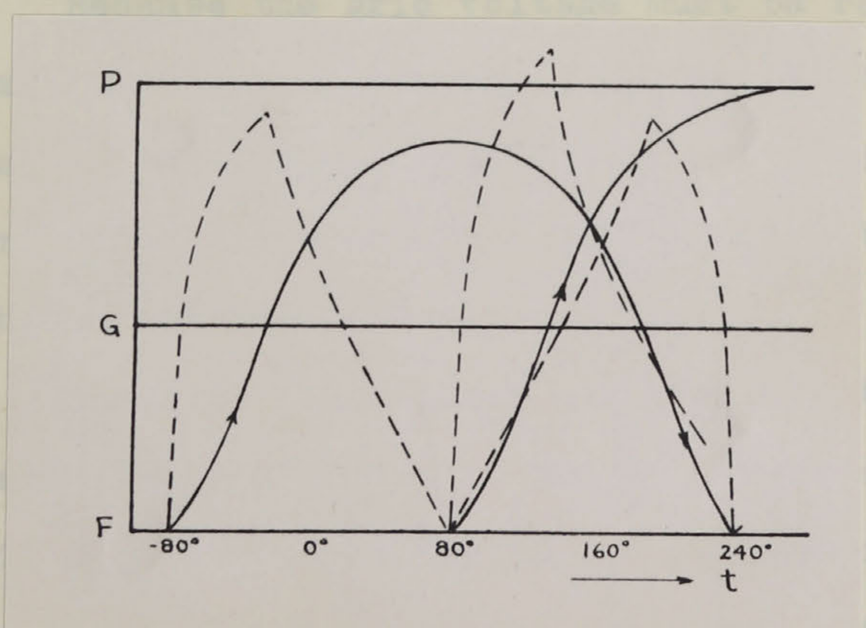


Fig. 35

Potapenko's final paper [49] deals with the influence of the heating current and the alternating potentials on the wavelength of the oscillations, and draws the final conclusions of the work.

The wavelength formula of Scheibe in almost all cases gives values higher than those obtained experimentally. This can be due to one or more of three possible causes which the formula does not consider:

(1) The effect of space-charge.

(2) The effect of the alternating potentials.

(3) The effect of initial velocity.

All three of these quantities vary with the emission current in a tube, so that wavelength logically varies with emission current.

All of Potapenko's work was done with the grid potential above saturation value, so that there can have been no effect due to space-charge. The effect of initial velocity is vanishingly small. The alternating potentials must therefore account for the major part of any discrepancies found.

Because the grid voltage must be raised to get the point of maximum oscillation, the B-K constant for the normal waves rises considerably with decrease of heating current. With the dwarf waves the reverse is the case, and the B-K constant falls with the heating current.

Epstein [53] has shown that exactly these conditions would result from the effect of the electrode alternating potentials. "This proves that as far as can be seen from the above investigations the difference between observed and calculated wavelengths is to be explained completely by the dependence of the wavelength on the amplitude of the alternating potentials appearing on the grid and plate of the tube during oscillations. It is not absolutely true that this dependence is always due to the alternating potentials where the grid voltage is not above the saturation value."

Potapenko concludes that the errors in the best wavelength formulae then amount to about 9% for neglecting the effect of the alternating potentials, about 3% for assuming plane instead of cylindrical electrodes, and about 3% for space charge and initial velocity corrections. Consequently in developing a formula it is more essential to consider the alternating potentials than it is to correct for the cylindrical shape of the electrodes.

The relatively small errors in applying the B-K or Scheibe formulae to the normal waves under all conditions proves, finally, that it is necessary to preserve the fundamental conception of Barkhausen and Kurz that the length of a normal wave corresponds to the period of an electron oscillation.

A very recent paper by Potapenko [54] outlines ideas which he is at present developing with regard to the relation between B-K and G-M oscillations. No definite conclusions are given.

Chapter VIII

Electron Oscillations as Gaseous Phenomena

A paper by L.L.Nettleton [55], which appeared in 1922, gave the following information:

"The work of Barkhausen and Kurz and of Gill and Morrell was done with so-called hard tubes, and these experimenters assumed they were dealing with purely electronic phenomena, and that no gaseous ionization was concerned."

"Using a typical circuit, with a tube continuously connected to a vacuum pump we have studied the effect on the oscillations of change of grid voltage, of electron current, and of gas pressure. It was found very unexpectedly that both the plate current and any sign of oscillation as indicated by Lecher wires ceased abruptly at very low pressures.

The indication is that a small amount of ionization is necessary to this type of oscillation. The kind of gas is unimportant, hydrogen, mercury vapor and air giving similar results.

Since the gas pressure at which the oscillation stops is so low (.00005 millimeters), there can be no connection with the mean free path of the ions, which at these pressures is many times greater than the dimensions of the tube. It is not likely that commercial tubes used by any other investigators are sufficiently exhausted to give any indication of the dropping off of the curves at the low pressure side."

"So far no satisfactory explanation has been found for the profound effect of such a small amount of gas on the behaviour of the tube."

This paper was the beginning of a controversy which has involved almost as much material as the entire subject of electron oscillations.

Side by side with many of the papers that have been considered in the past six chapters, a large number of them by the same authors as those reviewed, have appeared dozens of articles attempting to explain electron oscillations as either a function of the ionization in the tube, or due indirectly to it. Others have regarded the electron stream as a perfect gas, and have studied natural oscillation frequencies for such a gas.

Probably the most complete investigation of any phase of the matter is the paper of Langmuir and Tonks [56], which concerns the high frequency oscillations that can be detected in an ordinary mercury vapor discharge tube. These are often found to be of the same order of wavelength as the electron oscillations that have been dealt with, and a relation between the two is indeed conceivable.

It has been believed that a discussion of these papers would be out of place in the present thesis, because there has not been the slightest possibility of experimentally verifying the conceptions involved. Properly the subject would come under the general study of high frequency phenomena in gases, and should be dealt with individually. A fairly complete bibliography on the matter is included at the end of the thesis.

The state of chaos in which the problem is now enshrouded is very well indicated by the concluding paragraph of a paper of Karl K. Darrow in the Bell Technical Journal [57].

"To anyone desirous of penetrating through phenomena to fundamental laws, the situation as presented in this article (On High Frequency Phenomena in Gases) must seem deplorable. The laws of the high frequency discharge are almost purely empirical, either unexplained altogether, or explained only in a vague and qualitative way. Even the data do not form a complete or coherent system. For the remaining type of high-frequency glow not treated here - the so-called electrodeless discharge, in which high frequency magnetic as well as electric fields pervade the ionized and excited gas, the situation is yet more obscure. Still, if the reader will consult again the article which preceded this one [58], he will be reminded that considerable progress has already been made in interpreting by fundamental theory the events which happen when high frequency fields are applied to gas which is independently ionized by some other agent. This gives hopes of future success in extending the theory to the phenomena which occur when the high frequency fields are themselves the causes of the ionization."

The problem of high-frequency gaseous phenomena is one which at the present time should certainly very excellently reward serious research.

EXPERIMENTAL WORK

EXPERIMENTAL WORK

1. The object of the work.

A very common habit of experimenters on physical subjects is to attempt to find explanations or to develop theories to account for observed singular characteristics. The particular characteristic is not considered in its relation to others that would result from varying all possible parameters. This accusation may be directed especially to many of the workers on electron oscillations.

A single curve of plate current to grid voltage for one particular set of other conditions means very little, and gives no hint of most of the properties of an oscillator; yet such a curve is what Gill and Morrell drew all the conclusions for their first paper from. It is true that their mathematical theory was not designed to explain the peculiarities of this curve, however. The recent work of Gill that was discussed in chapter VII was started to explain a very particular form of working diagram of the type of Fig. 31, having grid voltage and grid current dimensions, in which the oscillation regions happened to run diagonally. If Gill's apparatus had given a working diagram with the oscillation regions parallel to either axis, as is very often the case, he would not have been able to obtain the different harmonic wavelengths at the same grid voltage by varying the emission, and undoubtedly would not have arrived at the same conclusions.

Hollmann's explanation of Fig. 27 has already been mentioned as probably unsuitable for a similar reason.

In the general case, the circuit of the electron oscillator includes four variables, which can control the characteristics. These are

(1) External circuit dimensions and constants.

(2) Grid potential.

(3) Plate potential.

(4) Filament heating current.

Emission current is often substituted for (4), but it is obviously a function itself of the grid voltage, and is not a primary parameter.

In addition to these, the two external variables of magnetic and electrostatic fields are available to demonstrate internal electronic actions where possible.

There are five quantities which are functions of one or more of these variables, and the variations of which give the indication of the effect of each of the above parameters on the operation of the oscillator. These are

(a) Wavelength of oscillations.

(b) Oscillation intensity.

(c) Plate current.

(d) Grid current.

(e) Emission.

All of these eleven items are considered with respect to a single tube. A complete assortment of tubes indicates four more variables:

(1) Electrode shapes and dimensions.

(2) Number and location of electrodes.

(3) Materials used, especially in the filament.

(4) Residual gas content of the tube.

In the very great majority of cases, these last four factors are beyond the exact control of the experimenter. He has available certain types of tubes which represent particular specifications for each of these. It is therefore only seldom possible to obtain oscillator characteristics as a continuous function of any one of them, with the possible exception of the last.

In view of this, we may say that the characteristics of a given tube are determined as fully as possible when the values of the five functions a, b, c, d, e have been determined continuously for all possible values of the first four variables.

An $I_a - E_g$ characteristic such as Fig. 8 expresses one function in terms of one variable. The dimension of the function is involved as well as the dimension of the variable, the curve consequently occupying two dimensions in space.

The working diagram of Fig. 31 expresses the existence or non-existence of one function in terms of two variables. The dimensions of the function are not given, so that the characteristic is again two-dimensional in space. If the oscillation regions of Fig. 31 were built up from the plane to a height at each point corresponding to the oscillation intensity at that point, the dimension of the function is expressed in the dimensions of two variables, and the characteristic is three-dimensional in space.

If now it were desired to show the continuous effect of a third variable,such as plate voltage,on merely the existence of the function,the previous dimension of intensity of oscillation could give place to plate voltage. The resulting three-dimensional model would indicate the regions of oscillation,without regard to the intensity of oscillation at any point.

But,if it were desired to express the intensity of oscillation as a continuous function of the three variables of grid voltage,plate voltage,and external circuit length,it would be necessary to make use of a fourth dimension,time. The problem would obviously be solved by taking a motion picture of the shape of the model as it varied with plate voltage.

To bring in the only remaining variable,filament current,and to express the oscillation intensity as a continuous function of four variables is beyond the scope of human ingenuity. A number of motion pictures could express the intensity as a continuous function of three variables, and as a point function of the fourth,but this cannot be extended to the desired condition.

Each separate function of the five would require an individual space-model,if it is a function of two or more variables.

In practice the problem is considerably simplified. Oscillation intensity is the only one of the functions we have any need of complete diagrams for. The others can all be referred by numerical tabulations to this one.

Also in practice plate voltage is not an instructive variable. By that I mean that if the plate voltage be varied either positively or negatively from zero, the normal effect on the oscillations is to affect the wavelength slightly due to the change in potential conditions in the grid-plate space, and to gradually reduce the oscillation intensity to zero. Positive plate voltage draws all the electrons to the plate and prevents oscillation entirely. Negative plate voltage moves a virtual cathode in the tube closer to the grid, and as this virtual cathode approaches the grid oscillations cease.

The two exceptions to the above generalization are the oscillations obtained by secondary emission, described by the second paper of Gill and Morrell, and the oscillations which have occasionally been obtained at high negative plate voltages, as in the case of Scheibe and Pierret. It is certainly true that this second type is not encountered with the majority of available tubes, and because the first type should be considered apart from the normal oscillations, we may satusfactorily carry out all experiments with the plate at the same potential as the filament.

The three-dimensional space model showing oscillation intensity as a function of an y two variables presents more information at a glance than any other form of graphical representation. We may regard it as a standard. Elimination of plate voltage as a significant variable has left three remaining variables to be dealt with. The space diagram can express only two of these at one time. The total characteristic must therefore consist of a number of space models involving any two of the variables, taken for chosen values of the third. As a result we have three distinct forms of space models:

(1) Those involving grid voltage and external circuit, taken for various values of filament current.

(2) Those involving grid voltage and filament current taken for various external circuits.

(3) Those involving external circuit and filament current taken for various values of grid voltage.

It will be seen that Potapenko's results were all of type (1), where only one value of filament current was considered. Undoubtedly his work would have been much more general and complete had he taken his working diagrams and space models for several values of filament current.

There is little or no information available on results of type (3). Some tubes will give several ranges of wavelength at constant grid voltage on varying the filament current, as was found by Gill (page 80), but others will not do so in general, and will show a single region of oscillation of almost constant wavelength throughout the range of safe filament currents values. The tubes used for the main work of the present thesis were of this type, although some of the tubes available gave results similar to those of Gill.

The main results of the present work have come under type (2).

The original intention of the work was to carry through the process of space models for a very large number of different sizes of external circuit,so as to obtain a practically complete oscillation characteristic for a single tube,or more than one. Where the external circuit is the individual variable, there are of course an infinite number of possible sizes,but considering a few generally indicates the trend of indefinite increasing of size.

In obtaining a three-dimensional model experimentally, the grid voltage is actually the only continuously variable quantity. A number of curves of oscillation intensity to grid voltage are taken for filament currents over the entire possible range at small intervals,and these "cross-sections" of the space model are used to construct the actual model in plasticine. To get the detail of each individual cross-section, probably from 20 to 50 readings are necessary on the average, where plate current,grid current and wavelength are measured at each point. Possibly 10 to 20 filament currents must be considered,depending on the nature of the oscillation regions encountered. Then from 5 to 20 different external circuits must be treated to get a suitably complete characteristic. Thus a minimum of 1,000 and a probable maximum of 20,000 sets of readings is necessary,each set involving the three quantities mentioned,so that from 3,000 to 60,000 individual figures are required to construct the diagram. If plate voltage were an important variable,a single diagram might becomesthe work of several years.

In view of these figures,this thesis has been able only to make a start towards its original objective.

We will return to these space models again when the experimental work is developed to that stage.

2. The Equipment.

Practically all of the apparatus used throughout this experimental work has been used previously by Moore [59,60,61] for similar investigations. Several of the two-dimensional characteristics for the tubes used were first determined by him[61], and he outlined their general propesties. In addition he constructed the minute wavemeters that will be mentioned later, and which have proved invaluable for rapid work. None of his curves was taken for an oscillator using an external circuit, however, and they have not been utilized.

The tubes on which all the preliminary work was done are of the type illustrated in Fig. 36. They are all identical in construction, although they carry the names of three manufacturers. Fotos, Ediswan and Marconi-Osram tubes are shown. Very few

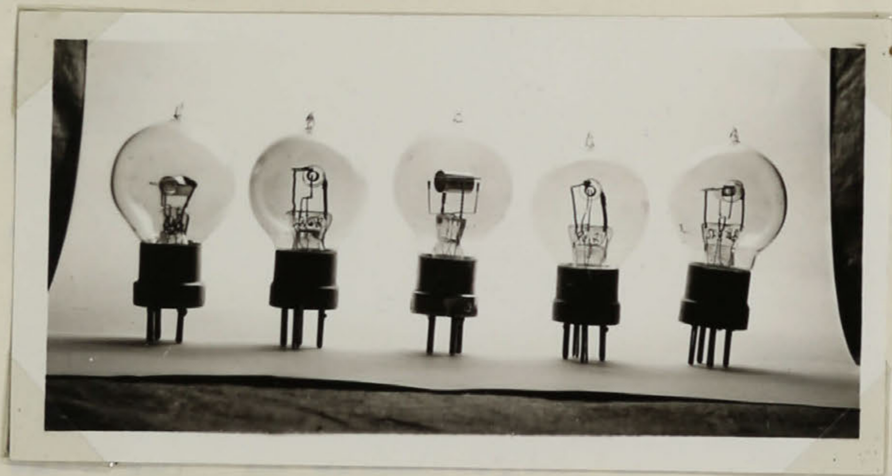


Fig. 36

of them possess a high degree of electrode symmetry. The plate diameter is 1.0 centimeters, and the grid diameter is 0.45 centimeters. The filament is tungsten, and has a rated heating current of 0.70 amperes. The vacuum is probably not exceptionally high, because at least two of the tubes have shown ionization, by a blue glow at high grid voltages.

The tubes used in obtaining the curves given throughout the experimental work were Marconi-Osram tubes of exactly the same internal construction and electrode dimensions, but have bakelite bases, and have been flashed to obtain a better vacuum.

Other tubes that have been available for testing are shown by Fig. 37.

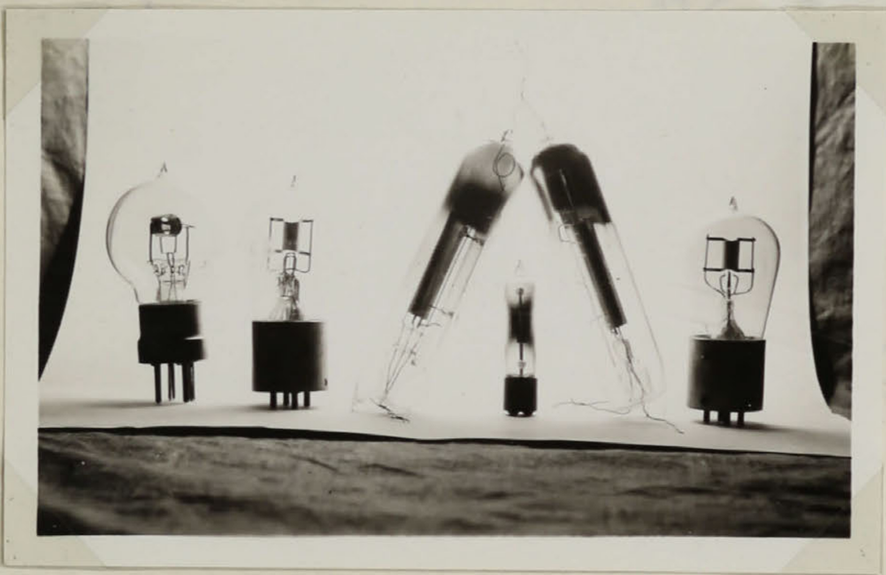


Fig. 37

That on the left is the same as those of Fig. 36. The tube at the right and the second from the left are type CG1162, being U.S.Navy transmitting tubes. They have a high degree of plate and grid symmetry, but have a spiral filament, which seems to affect their operation. Normal filament current is about 1.25 amperes. The third and fifth tubes from the left are two of a group which were expecially built by the Northern Electric company for test purposes. They have grids wound of wire .07" in diameter, but unfortunately their plate diameter to grid diameter ratio is slightly less than 2, and probably for this reason they do not exhibit any oscillation regions.

A number of peanut tubes with varying pitch of grid winding have also been at hand, but have not been tested. The standard UY227's and UY224's, as well as Western Electric 245A's, UX222's and UV199's have been tested briefly merely to indicate the possibility of obtaining oscillations from them.

Several arrangements of the apparatus forming the test circuit were made, in the attempt to find that which would be

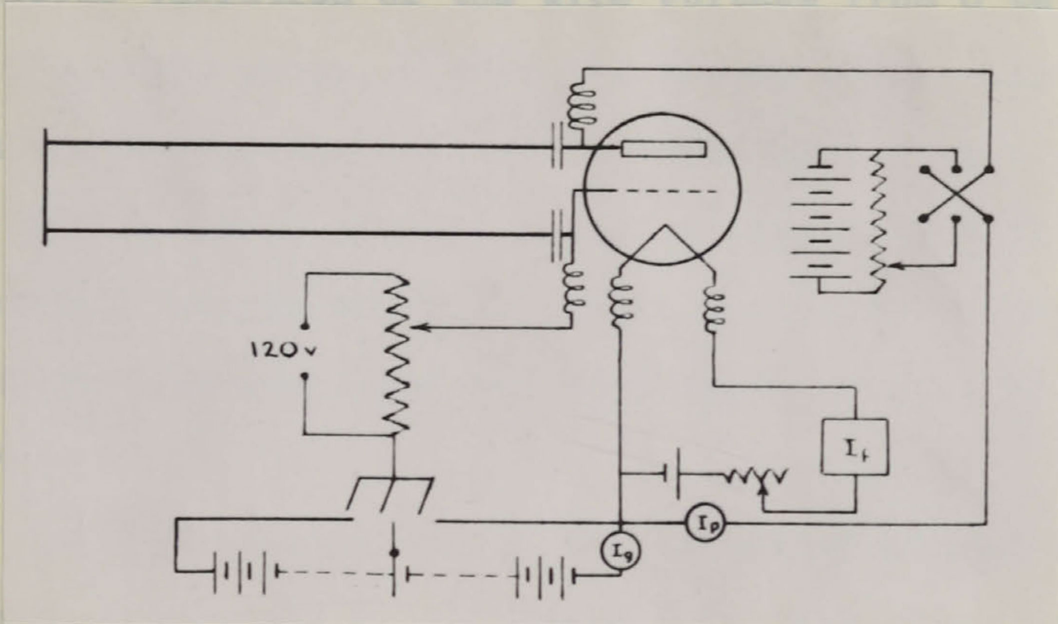


Fig. 38

most convenient for experimental work. The general layout finally arrived at and used throughout is that of Fig. 38. Ease in experimenting requires principally that any desired voltages be rapidly available, and that conditions remain steady during the time readings are being taken.

Although zero plate voltage was used for most of the work, a potentiometer and reversing switch is included to allow the application of up to 45 volts positive or negative on the plate, so that the negligible effect of this voltage can be checked as required.

The grid voltage supply consists of 180 volts of dry batteries, which are connected to switches so that 0, 90, or 180 volts can be taken off easily. Between the output of the switches and the grid of the tube is placed the output of a potentiometer,across which the 120 volt battery supply of the laboratory is connected. This potentiometer allows continuous variation of the grid voltage from 0 to 120 volts, from 90 to 210 volts,or from 180 to 300 volts,according to which section of the battery it is in series with.

The filament circuit consists simply of a rheostat and battery supply,together with a specially constructed meter that magnifies small current variations,as will be described later.

Radio frequency chokes are connected in all leads, although experiment proves definitely that where an external circuit is used,they have not the slightest detectable effect on the oscillation intensity. Where no resonant circuit is used,and the potentials are the only connections made to the tube electrodes,the filament chokes become important. The grid and plate chokes seem to be of very little importance in any case. Experimenters as a rule have not used such chokes. Experiments were made with tuned chokes in the filament circuit, with no resonant circuit at the grid and plate,and the oscillation intensity was found to have fairly marked variation with the tuning of the chokes.

Fig. 39 is a curve of oscillation intensity to dial reading,for a tuned choke consisting of a .00005 mfd. variable condenser with a one-half inch inductance,connected in the negative filament lead of a CG1162 tube. The tube is operated with the plate entirely free,and oscillation intensity is measured on a thermo-couple connected to two short Lecher leads from the grid and positive filament lead of the tube. These leads do not constitute a resonant circuit, because the grid voltage is so low that the electron frequency is much lower than the natural frequency of the leads.

With a similar choke in the negative lead, the curve of

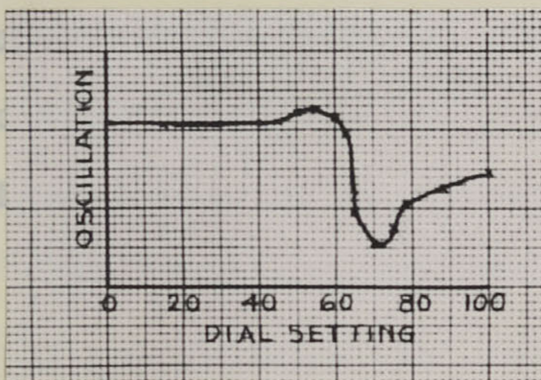


Fig. 39

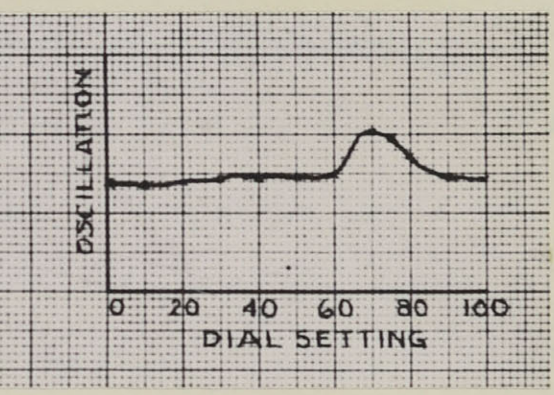


Fig. 40

Fig. 40 results. It is to be noted that for this curve the intensity is at a maximum for the scale setting that gave a minimum in Fig. 39. Evidently resonance occurs at that setting. Probably due to the connection of one Lecher wire to the positive filament terminal, resonance in the one case aids the oscillations by preventing loss of oscillatory power externally, while in the other case resonance chokes out some high frequency currents which normally increase the oscillation.

Similar tests made on the grid choke in exactly the same circuit indicated no observable variation of intensity with the tuning of the choke.

The means of connecting the Lecher system to the tube, and the point of application of the fixed potentials both permit of several variations. Possibly the most generally used method is to connect the Lechers directly to the tube and to place a blocking condenser in the bridge. The potentials in this case are applied to the Lechers. This arrangement now permits of variation of the position of application of the grid and plate potentials, which seems to be of some importance. It is also possible in this case to connect the potential leads to the two sides of the bridge. Since the bridge is presumed to generally be a node of the system, it is theoretically the correct place to apply these potentials. Grechowa [62] has considered some of the possibilities suggested here.

The above general method was used for much of the early work in the present case, for several different points of application of the potentials. It is, however, rather awkward to have a condenser always in the bridge, and the method was changed to that illustrated in the diagram of Fig. 38. Here the potentials are connected directly to the electrodes, and blocking condensers are placed immediately at the electrodes in the two sides of the Lecher system. The bridge now becomes simply a short-circuit of the system, and it is possible to determine the effect of different types of bridge without having the complicating factor of condenser impedance to consider. It is believed that this method is most satisfactory for general work, although that mentioned above would permit of much additional experimental work.

The Lecher system was constructed of $\frac{1}{4}$" brass rod, the two sides being spaced 5 centimeters apart. At the one end these were bolted firmly to the terminals of the Sangamo .002 mfd blocking condensers. The condensers themselves were bolted to individual sockets in which the tube prongs rested.

Experimental work indicates that the nature of the bridge used is very important. For the most part, it is doubtful if a sliding bridge is advisable at all. Telescopic Lechers with the bridge consisting of the end short-circuit are undoubtedly the best solution of the problem. Particularly is this the case where the Lecher wires are large and close together, so that their inductance and distributed capacity are large. In this case it appears that a bridge of any considerable impedance does not eliminate the end effect of any section of the wires beyond it. If the Lecher wires are small and are fairly well separated, a low impedance bridge does effectively vary the constants of the circuit.

The type of bridge used for the first experimental work here is illustrated roughly in Fig. 42. A Western Electric thermo-couple is fitted with heavy copper arms that allow it to rest on the Lecher wires and slide along them, the arms making continuous contact. Figs. 43 and 44 show an adaptation of this method, where a blocking condenser is used in the bridge in series with the thermo-couple.

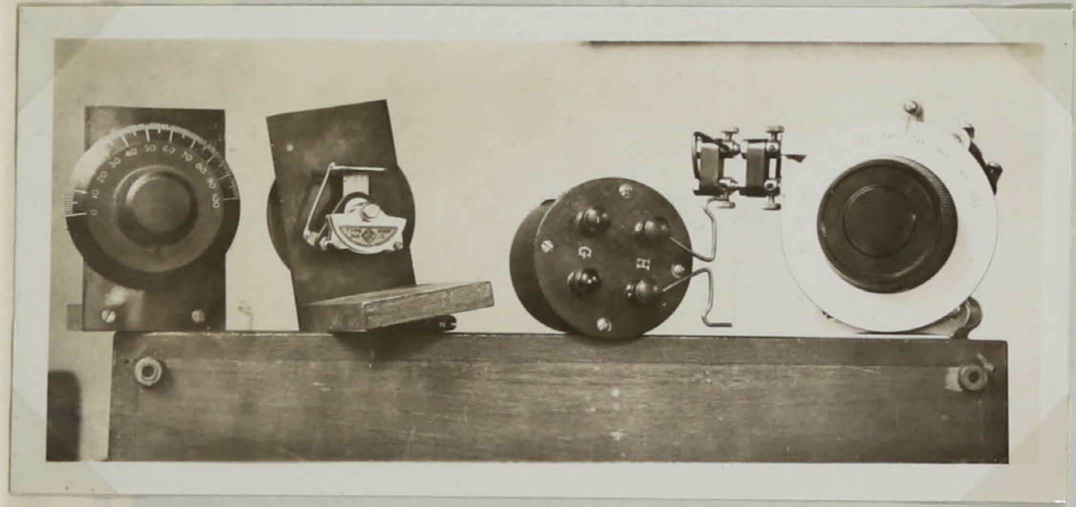


Fig. 42

Another type of bridge used consisted of a .005 mfd Sangamo condenser bolted to two copper strips which were wound twice around the Lechers on either side. This does not allow intensity measurements in the bridge.

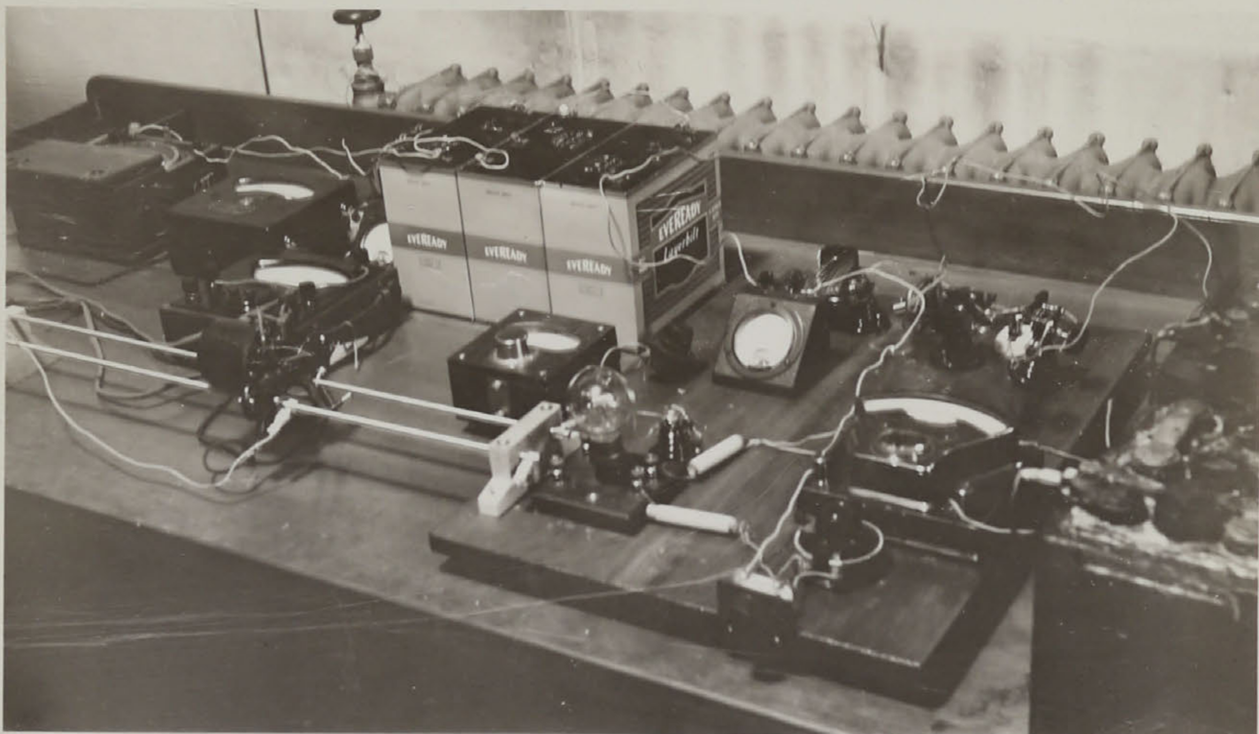


Fig. 43

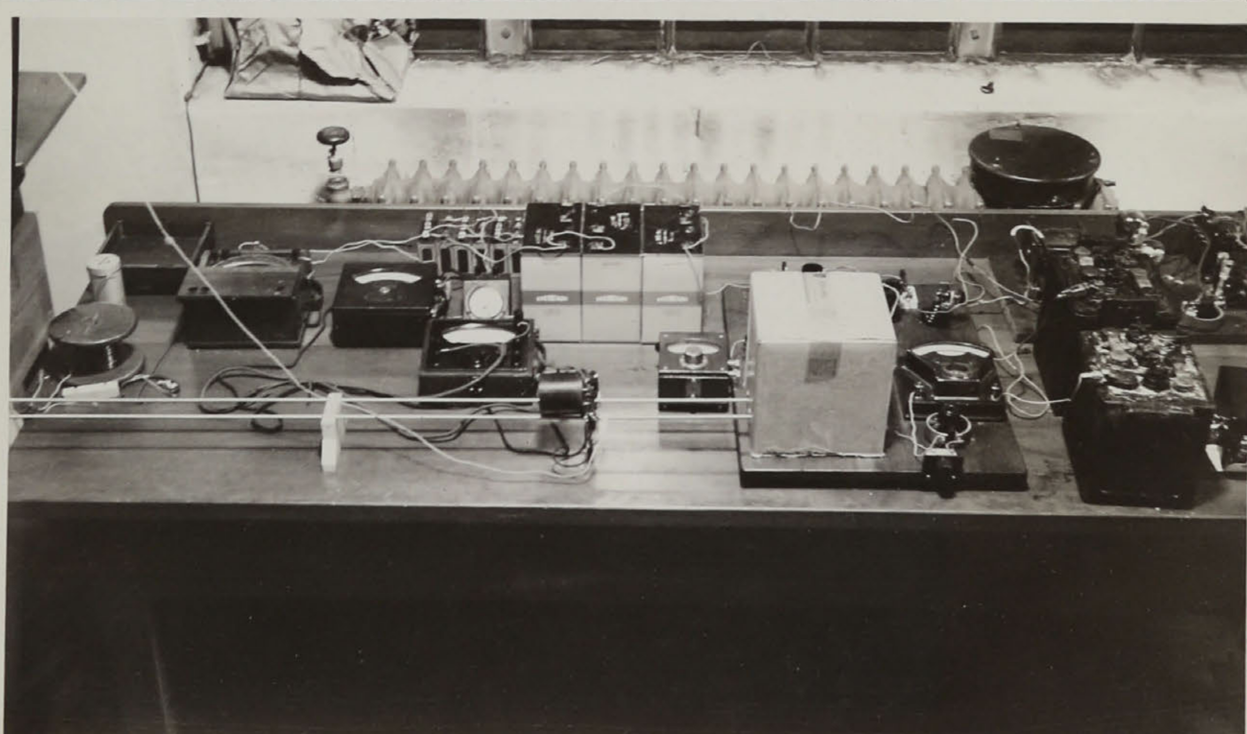


Fig. 44

Various methods for direct short-circuit constitute the final possibilities. The simplest is a continuous copper strip wound around the two rods. A paper by Tonks [63] has dealt with the question of the effect of the free ends in the case where a shorting bridge is used, and suggests that a double bridge with a second shorting bar one eighth of a wavelength behind the first eliminates all end effects.

It is probable that end effects are essentially eliminated if the bridge takes the form of a plate of several inches width along the Lechers.

For obtaining tube characteristics, however, the use of a sliding bridge is not recommended, and no free ends should ever exist during experiment.

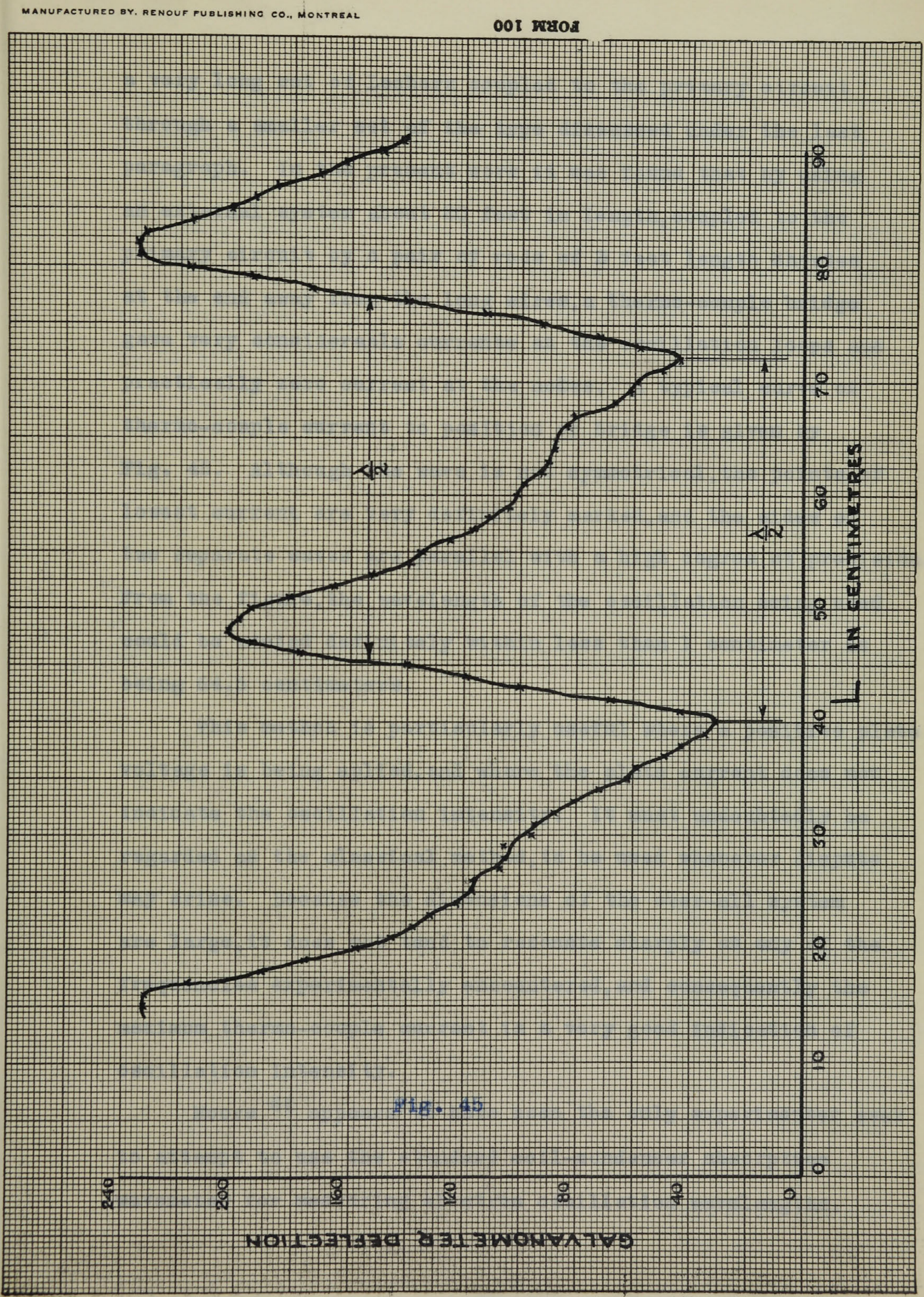
3. Measurement of wavelength.

As was mentioned on page 16 of Chapter II of the last section, the method of standing waves on wires as a means of measuring wavelength has been known since the beginning of the century. Even today it remains the standard for all high frequency measurements.

Three variations of this method have been compared in the present work. In the first place, Barkhausen and Kurz measured wavelength on the external circuit connected directly to the tube, by observing the effect on the plate current and bridge current of moving the bridge. This method is certainly the most accurate, and if it were not for the effect of the bridge position on the operation of the oscillator, would be used exclusively. Potapenko's measurement of wavelength from the simplified working diagram of Fig. 32 are based on exactly this principle. Rough wavelength measurements can be easily based on it by moving the hand along the Lecher system, and observing the distance apart of points at which the plate current or oscillation intensity becomes a minimum. Gill and Morrell took many of their wavelength measurements in this way by moving a knife blade along the wires. Its position for the points of minimum plate current could be determined within one-half centimeter, and the wavelengths could thus be measured with no more than 1% error.

A second variation of the method is to use a small Lecher system of the same order of dimension of the circuit on the tube, and to observe wavelength by the critical positions of a bridge moved along it. This method has several disadvantages unless the external circuit on the tube is fairly large. Principally, the pick-up in such a circuit is very small, and high frequency currents induced in it are not easily measured. Some workers have been able to fix the critical positions of the bridge on this coupled circuit by variations in plate current or oscillating current in the oscillator, and have obtained accurate results from this. The equipment tested here, however, did not react in this way, and the method could not be used. Although nodes and loops along such a system could be definitely observed with a thermo-couple bridge as in Fig. 42, the wavelength could not be fixed within 2 to 4 centimeters in any case. Such low precision is of no experimental value.

The final adaptation of the coupled circuit is to use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λ/2

Fig. 45

a very long set of Lechers coupled to the primary circuit through a smaller set of the type discussed under the last paragraph. In the present work it was found that by using an external system about 20 feet in length, coupled to the primary circuit by a pair of rods of 3 feet length shorted at the end away from the long wires, a thermo-couple bridge gave very considerable currents at the oscillation loops and practically zero current at the nodes. A typical curve of thermo-couple current to position of bridge is given by Fig. 45. Although the wave is not symmetrical, the points of lowest current are very definitely marked, and the sides of two separate waves are parallel with a high degree of precision. From the figure, the wavelength of the oscillation being used could be stated definitely within less than 1 centimeter as being 64.5 centimeters.

This method is particularly useful where a positive plate voltage is being aplied, and where the plate current does not indicate the oscillation intensity. It must undoubtedly be regarded as the classical method, to be used whenever dispute may arise. Because the dimensions of the over-all system are large, it does not tend to resonate sharply at any of the frequencies experimentally encountered, and consequently the maximum thermo-couple current is a very good indication of oscillation intensity.

Moore [61] appears to have been the only experimenter ever to attempt to use the standard coil-condenser absorption wavemeter for measuring electron oscillation wavelengths.

Using a General Radio midget condenser of capacity .00005mfd, he found that an inductance consisting of about one inch of wire across two projecting parts of the condenser made a wavemeter resonant between 55 centimeters and 150 centimeters. A similar condenser with two of the rotor plates removed, and with the inductance consisting of the shortest possible connection between rotor and stator showed resonance between 45 centimeters and 60 centimeters.

He then found that if one of these wavemeters were tuned to the resonant frequency of an electron oscillator, a kick in the plate current could be very easily observed. By observing these kicks and measuring corresponding wavelengths accurately on a Lecher system, he was able to calibrate the wavemeters, obtaining the curves of Fig. 46. The two wavemeters themselves are seen at the left of Fig. 42, and the one inch inductance in the one case can be noticed.

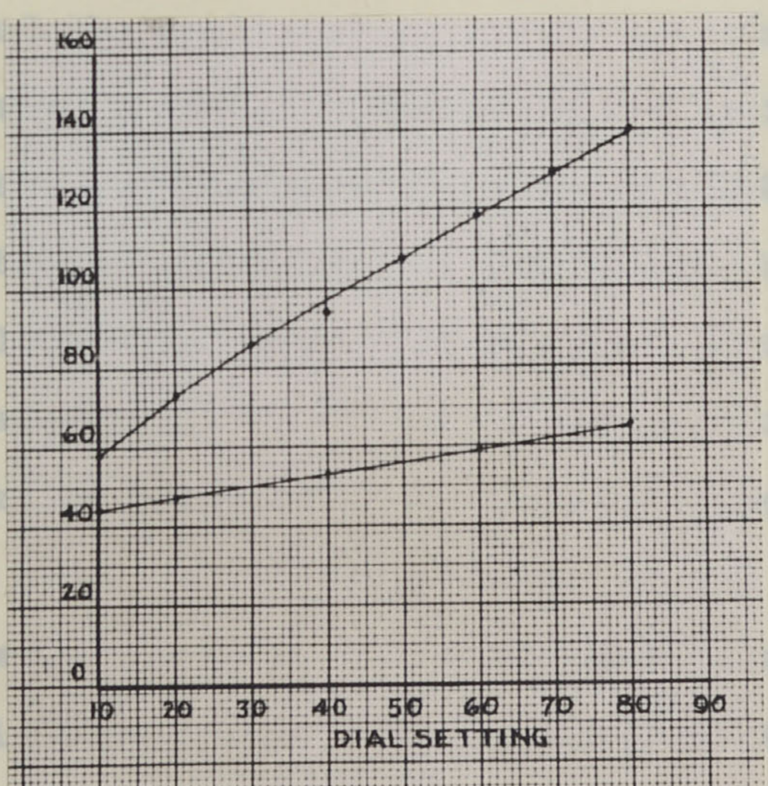


Fig. 46

The value of such wavemeters is tremendous from the point of view of time saved. Measuring wavelengths on Lecher systems requires on the average two or three minutes for each individual reading, or longer if very high accuracy is desired. Measurements with the absorption wavemeters can be made in a few seconds in most cases. There is, however, one serious limitation to their use. Some regions of oscillation are found in which the plate current kick at resonance is very very small, and in the extreme, there are cases where the kick cannot be detected at all. The regions obtained at low grid voltage and high filament current show this characteristic very strongly.

The oscillation region of shortest wavelength encountered for any one value of filament current generally has the appearance of being 'unstable'. It is very sensitive to the presence of the hand around the Lecher system, and the oscillations are immediately stopped by touching the wires. In this case, it is sometimes possible to completely stop oscillation by tuning one of the small wavemeters to resonance, even though the meter be several inches from the tube. Oscillations of longer wavelength for the same value of filament current appear to increase in 'stability' with the wavelength, and the region of longest wavelength for high filament current usually exhibits the characteristic mentioned, of showing no plate current kick at wavemeter resonance. At the same time the oscillator becomes less sensitive to the presence of the hand, and the oscillations are merely reduced, not stopped, by touching the Lecher system. The long externally coupled wires must be used to measure the wavelength in these stable regions.

4. The nature of the effect of the heating current.

The results obtained by Gill [43], and those shown by

Moore [61] prove that at least in some cases variation of filament current may cause oscillation to occur in different regions. Moore's figures indicate that changes in filament current of 5 milliamperes can often cause a change from non-oscillation to strong oscillation. Whenever a characteristic is obtained under constant filament current conditions, it is obviously necessary that this constancy be maintained within 1 or 2 milliamperes. In taking a space model characteristic, $I_a - E_g$ curves are plotted for several values of constant filament current, so that the present work has required some means of maintaining this constancy. The device of Fig. 47 has been used for this purpose. Its principle is the fact that the UV199 tube has a very steep characteristic of plate current to filament current, at constant plate voltage. By passing the filament current of the oscillator tube through

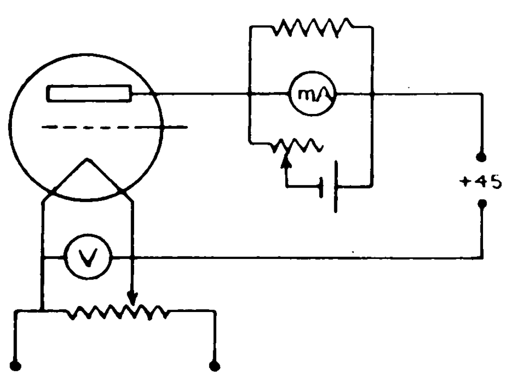


Fig. 47

a resistance, and using the resultant voltage drop to heat the filament of a UV199, any small variations in the oscillator filament current can be magnified in the plate current of the UV199. Then by using a reverse current through the plate milliameter of the 199 to null the normal plate current value, a very low range milliameter can be used to measure the resultant current. Close adjustment of the reverse current, and suitable choice of the low range meter will allow any desired increment of plate current to be magnified to the full scale of the meter. Consequently the same is true for any chosen increment of oscillator filament current.

The circuit of Fig. 47 illustrates all these characteristics as described; in addition, it is necessary to have a low resistance shunt that can be connected across the meter to keep the current through it low before the reverse current has been adjusted to a suitable value.

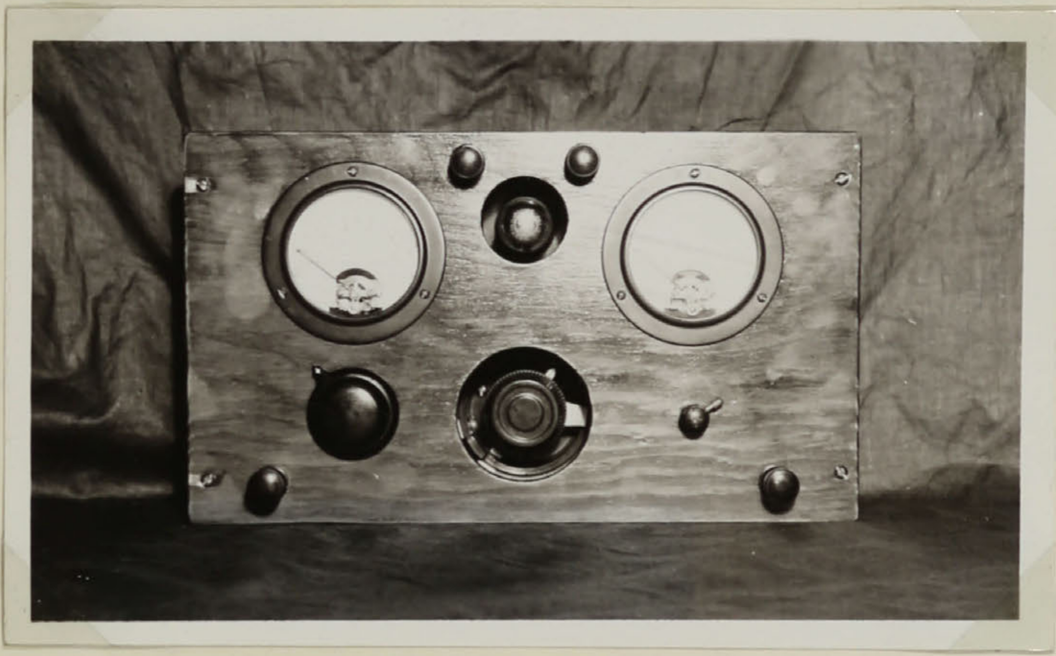


Fig. 48

Fig. 48 illustrates the final form taken by this equipment. The reverse current is supplied by a 1.5 volt battery, in series with a 5000 ohm variable resistance at the lower left of the photograph. The resistance at lower center is that through which the oscillator filament current flows. For various values of filament current this resistance is adjusted to keep the filament voltage on the 199 at 3.3 volts, where its characteristic is steepest. The upper right-hand meter is the filament voltmeter. At the left is the plate milliameter which is a 0 - 1 milliampere range meter. This was found to give all the sensitivity desired. One milliampere change of oscillator filament current caused a movement of two scale divisions on the plate milliameter, so that check could easily be made within one half milliampere. A Weston 0-1000 milliameter was used for rough adjustments of the filament current.

There are four characteristics of actual filaments which tend to complicate electronic problems. These are

(1) The initial velocity of the electrons.

(2) The voltage drop along the filament.

(3) The magnetic field caused by the heating current.

(4) The mutual repulsion of the electrons.

O.W.Richardson in the Classic work on "Emmssion of Electricity from Hot Bodies" deals at great length with all of these.

Item (4) causes an effect that is not easily calculated or determined experimentally. Item (3) can be calculated mathematically; the force produced by this magnetic field tends to move the electrons parallel to the filament, in the opposite direction to that in which the filament current flows. There is no influence in this case on the radial velocity of the electron, and since the passage time of the electron depends solely on the radial velocities, and not on the path length (see 8 below), the magnetic field of the filament does not affect the wavelength of oscillations. The displacement produced by it is so small in any case, that it need not be considered.

Gill and Morrell (page 31) mentioned the influence of the voltage drop along the filament. Instead of dealing with a single stream of electrons actuated by a grid voltage V, there are a number of streams moving under potentials of from V to V - 4 volts. If the grid potential and the filament potential have a common negative terminal, the streams moving under the potential V - 4 volts to the grid will be influenced by a potential of -4 volts on the plate, while for the streams at grid voltage V, the plate voltage will be zero. Consequently there are slightly different oscillation conditions over the possible range.

No other references to the effect of this potential drop have been found. It seems to the writer, however, that the fact of maintenance of oscillations over a range of wavelengths for the same grid voltage is partially due to it. Because of the existence of the streams actuated by different potentials, the oscillator should be able to produce natural electron oscillations over the wavelength range corresponding to the voltage range. The G-M effect of the control of the external circuit on wavelength, or the range of values of the ratio of the period of a resonant circuit to the natural electron oscillation period should extend from the extreme points of the wavelength range corresponding to the voltage range. Hence the apparent range of values of the ratio should experimentally be found to be greater than would be calculated from a formula such as Kapzov's. And this effect is greater the lower the grid voltage, since the percentage variation due to filament voltage will be higher, and the wavelength range corresponding will be greater.

It has been apparent from the experimental work of this thesis that electron oscillations can best be obtained from the tubes that were used when operating at the knee of the saturation curve. Oscillations have not been found when complete saturation has set in, nor do they tend to exist at low grid voltages and no saturation. The process of saturation, but not the existence of saturation, seems to be essential to oscillation in the general case.

In view of the following quotation from Richardson, the factors listed on page 122, although they complicate the oscillation process, may at the same time be responsible for the possibility of oscillation.

"That the mutual repulsion of the electrons, the magnetic field due to the heating current, and the drop of potential along the wire are the chief general factors which prevent the attainment of saturation is strikingly shown by some recent experiments of Schottky [64]. Using concentric cylinders, the thermionic currents with small differences of potential both accelerating and retarding, were measured under conditions such that both the heating current and the consequent drop of potential were cut out at the instant of measurement. By means of a suitable "in and out" switch, operating continuously, matters were arranged so that no appreciable variation of the temperature of the wire ensued thereby. Under these conditions the drop of potential along the filament and the magnetic field are eliminated, and it was found that the current saturated at zero potential difference, except for an effect which was smaller the lower the temperature and the smaller the current, arising from the mutual repulsion of the electrons."

"Schlichter [65] by using methods of heating the electrode which do not involve the passage of an electric current has been able to show that the electron current with 220 volts driving potential is only about 10 to 20 percent greater than under zero potential difference, when the hot metal has been thoroughly glowed out."

Consequently, if oscillations cannot occur at full saturation, we owe their existence entirely to the disturbing effects which prevent the attainment of saturation.

If the initial velocity of the electrons be expressed in volts, we have an exact measure of the effect of the velocity on the wavelength. It is evident that whatever this velocity may be, its effect is to shorten wavelength.

Davisson and Germer [66] and others have demonstrated experimentally that a Maxwellian distribution of velocity exists among the electrons emitted by a filament. Working on this basis, it should be possible to find the velocity in volts at which the majority of the electrons are emitted.

Maxwellian distribution is expressed by the fact that the number of electrons having velocities between u and $u + du$ satisfies the formula

$$N_u \, du = N \, 2h \, m \, u \, e^{-hmu^2}$$

where N_u is the number of electrons at velocity u, N is the total number in unit time, h is Planck's constant, m and e are the mass and charge for the electron. The general shape of the Maxwell curve is shown by Fig. 49. It states that no electrons are emitted with zero velocity and none with infinite velocity. At some finite value, the number of electrons emitted is a maximum. The number emitted at velocities greater or less than this value decreases as the velocity considered is greater or less respectively. It is apparent from this that, barring other disturbing factors, a voltage V_1 retarding the electrons will turn back all those with velocities less than a value corresponding to this voltage. The plate current for retarding voltage V_1 will be the integral from this velocity to infinity of the Maxwell curve. As V_1 is varied, the limits of the integral vary. The plate current for $V_1 = 0$ will be the total area under the Maxwell curve, and the plate current at any other velocity will have a relative magnitude equal to the area under the curve from infinity down to that velocity. Consequently the first differential of the plate current curve should give a Maxwell distribution curve, and should indicate the favored velocity.

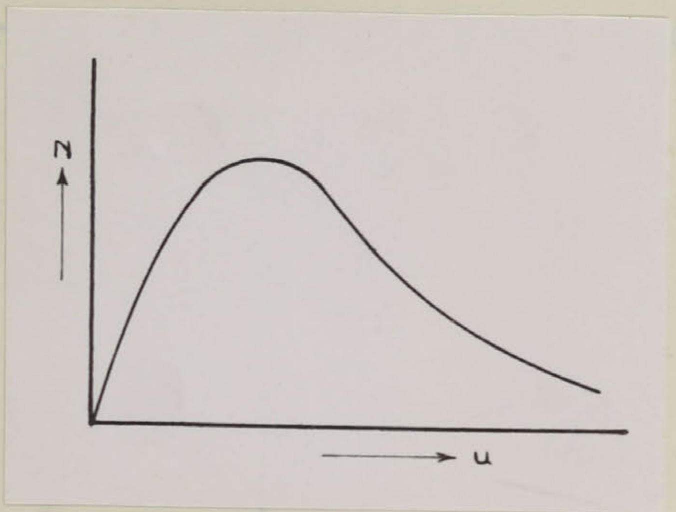


Fig. 49

This would be the case if the potential V_1 were constant along the length of the filament. Actually we must bring into consideration the voltage drop due to the filament potential.

Suppose grid voltage $-V_1$ with respect to the negative end of the filament is used. We will differentiate the grid current curve rather than the plate current curve. Then Fig. 50

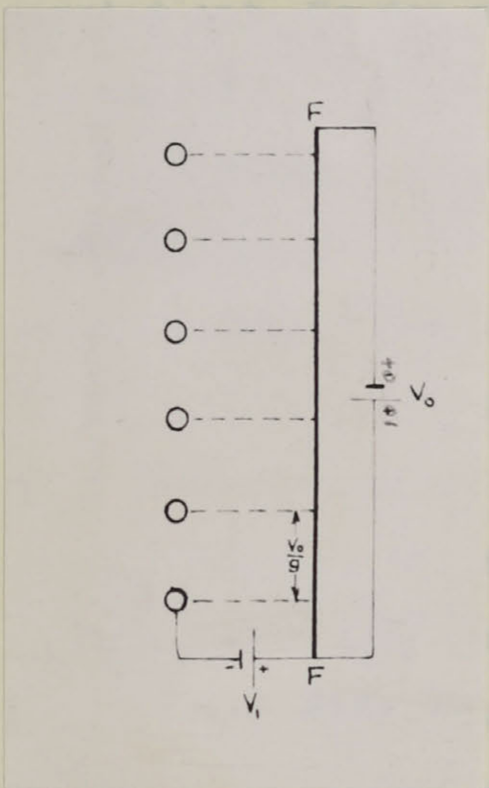


Fig. 50

shows a typical cross-section of the tube. The retarding voltage at the positive end of the filament is $V_1 + V_o$, where V_o is the filament potential. If there are g grid wires, the retarding potential at the second grid wire from the positive end of the filament is $V_1 + \frac{g-1}{g} V_o$, and there is a similar expression for each of the other grid wires. For the nth wire from the negative end of the filament, this becomes $V_1 + \frac{n}{g} V_o$. The velocity corresponding to this is

$$\sqrt{2 \frac{e}{m} \sqrt{V_1 + \frac{n}{g} V_o}}$$

and the grid current to that particular grid wire is the integral from this velocity to infinity of the Maxwell curve. Finally, the total current to the n grid wires is the integral between the limits 0 and n of the above integral, or

$$I = \int_0^n \int_{k\sqrt{V_1+\frac{n}{g} V_o}}^{\infty} 2\,N\,h\,m\,u\,e^{-hmu^2}\,du$$

Consequently the second differential of the grid current curve taken for various values of V_1 should give the shape of the distribution curve,and the velocity in volts at which the maximum number of electrons is emitted.

Such was the basis on which a few experiments were carried out. So far as is known they have never been carried out before.

At first the grid current curve was taken for grid voltage intervals of a quarter of a volt,and the resulting second differential curve (as the rate of change of slope at all points) did not show a maximum. Later it was found that the velocity at which the maximum distribution occurs is generally of the order of less than half a volt. Richardson mentions this fact briefly in his text. The final curve was plotted from grid current values taken at every .01 volts from 0 to 0.5 volts,and for every .02 volts from 0.5 to 1.0 volts. The resultant curve was plotted,an equivalent smooth curve drawn for calculation purposes,and the second differential curve obtained by direct observation of the rate of change of slope along the curve. The plotting was first done on a very large scale,to allow sufficient accuracy. The curve of Fig. 51 is the result on a smaller scale,and indicates that the maximum number of electrons have a velocity of about 0.17 volts.

This value is so small that it can never account for any observed discrpancies between experimental and theoretical wavelengths,and there is no need of considering the question further. The value was found to rise slightly for increased filament currents,to a maximum of about 0.22 volts. The figure of 0.17 resulted from a filament current of 0.63 amperes.

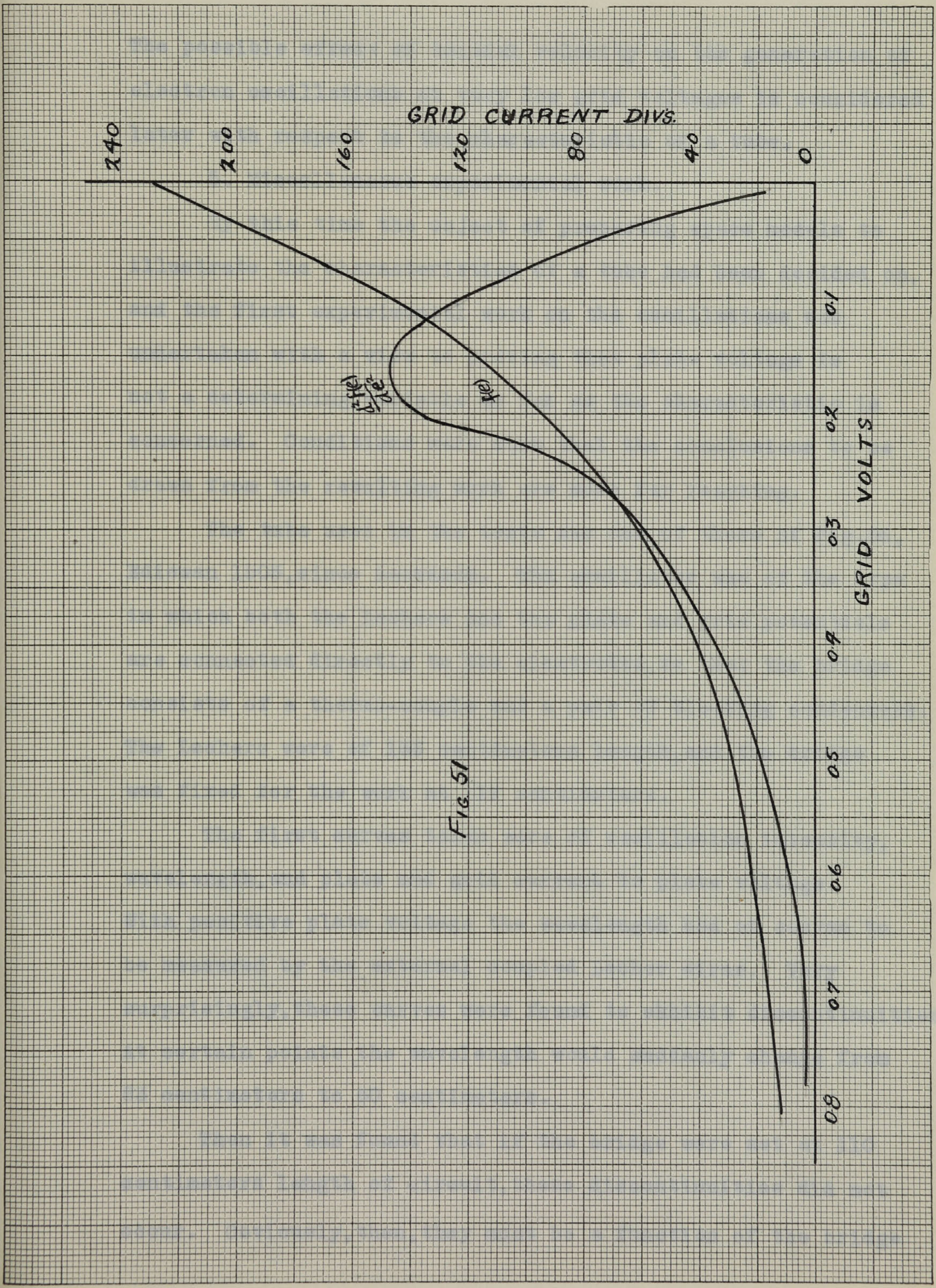

GRID CURRENT DIVS.
240
200
160
120
80
40
0
GRID VOLTS
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
f(e)
$\frac{d^2 f(e)}{de^2}$

Fig. 51

The possible effect of initial velocity on the generation of electron oscillations at very low grid voltages is considered later with respect to the characteristic of a tube.

5. Miscellaneous experimental work.

By this time the object of preparing space models to illustrate the characteristics of a tube had been decided on, and the first experimental work on the oscillations was undertaken with a view to proving that plate voltage is not a determining variable as far as the characteristic is concerned. Conditions were such that the conclusions to be drawn from the resulting work are more far reaching.

The tube used in the tests was one of those of Fig.36, Ediswan 1505,since deceased. The oscillator was of the type in which both the Lechers and the plate and grid potentials are connected directly to the electrodes,so that the bridge consists of a thermo-couple and a pair of blocking condensers. The Lechers were of 135 centimeters length,and the bridge was fixed for the work at 119 centimeters.

The first curves taken were of oscillation intensity, wavelength,and plate and grid current to plate voltage. With positive plate voltage the wavelength had of course to be measured by the external coupled Lecher wires. Very surprisingly,these curves were found to exhibit discontinuities. At certain points the wavelength would suddenly change from 83 centimeters to 50 centimeters.

Then it was found that if the bridge were set at 110 centimeters length of circuit,these discontinuities did not occur. Obviously,then,they must be a function of the bridge

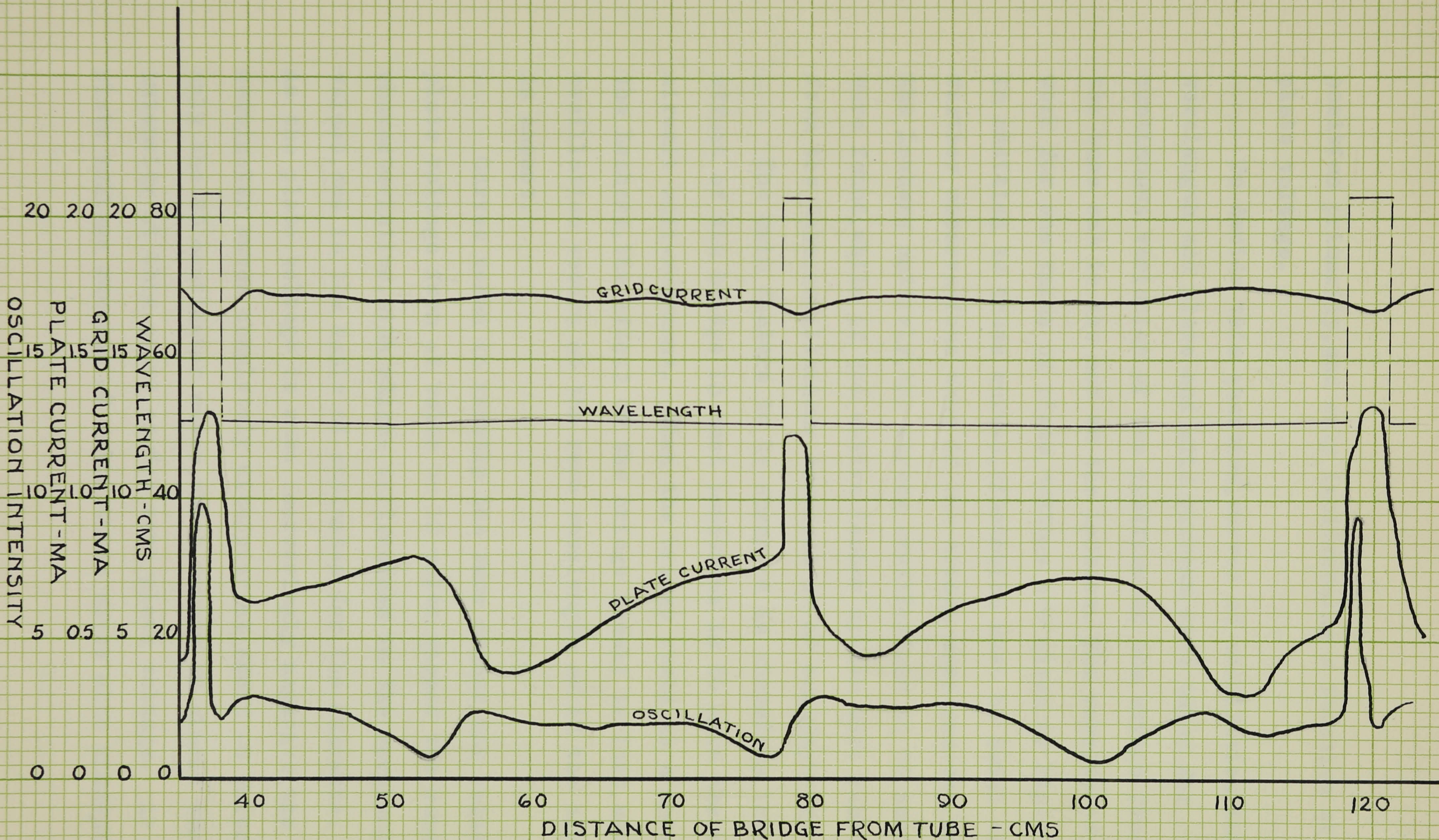

GRID CURRENT
WAVELENGTH
PLATE CURRENT
OSCILLATION
OSCILLATION INTENSITY
PLATE CURRENT - MA
GRID CURRENT - MA
WAVELENGTH - CMS
20 2.0 20 80
15 1.5 15 60
10 1.0 10 40
5 0.5 5 20
0 0 0 0
40
50
60
70
80
90
100
110
120
DISTANCE OF BRIDGE FROM TUBE - CMS

FIG. 52

position primarily, and only incidentally a function of the plate voltage.

To decide this question, curves of oscillation intensity, wavelength and plate and grid current were taken for continuous variation of the position of the bridge from next the tube out to the end of the Lechers. The results of this work for one value of plate voltage are given by Fig. 52. In addition to these curves, discussion must be based on the further observations that if the bridge were removed from the Lechers entirely, the strong oscillations at 83 centimeters were found, while if the entire Lecher system were removed from the tube, oscillations occurred at 50 centimeters.

The main feature to be observed is therefore that the effect of the bridge in most positions is to make the external circuit anti-resonant. When the bridge rests at a node of the Lechers, the effect of the bridge itself is lost, and oscillation occurs at the same wavelength as if the bridge is absent.

Curves taken in exactly the same manner for values of plate voltage from -7 volts to 10 volts showed the same general characteristics, with slight differences in the wavelength values, and in the scale of ordinates for the currents. As the plate voltage is made increasingly negative, the 50 centimeter waves completely disappear at about -6 volts, leaving only the 83 centimeter waves, which remain of almost the same intensity at this point as for zero plate voltage. As the plate voltage reaches -8 volts, these waves also disappear, and no oscillations of any kind can be detected.

When the plate voltage is increased positively, oscillation intensity increases for plate voltages up to about 3 volts, then gradually falls off to zero for both types of waves, and finally reaches zero at between 15 and 20 volts.

The desired result is therefore definitely illustrated, that plate voltage is a quantitative rather than a qualitative variable.

In addition to this there are the following unexpected indications:

(1) A resonant external circuit is not formed by the Lecher wires to the bridge and the bridge itself. If this were the case, continuous displacement of the bridge should produce a continuous wavelength change, over the possible regions that a working diagram of the Potapenko type would demonstrate.

This bridge consisted of the 600 ohm heater section of a thermo-couple, in series with two Sangamo .001 mfd mica condensers. Its overall impedance at the high frequency used may have amounted to thousands of ohms. To examine the effect on the wavelength, two other forms of bridge were tested. The first consisted of another thermo-couple of heater resistance 1.5 ohms, in series with the same two condensers. The second consisted of a single .002 mfd condenser moving directly on the rods. There is no indication of any greater variation of wavelength with bridge position for either of these.

The fact mentioned on the last page that the 83 centimeter wave is characteristic, of the Lecher system as a whole, while the 50 centimeter wave is characteristic of the tube itself, leads to the conclusion that has been mentioned before that the use of a bridge of this type is not to be recommended, and that to perfectly investigate the effect of external circuit changes, the external circuit should have no free ends.

(2) The intensity of the 83 centimeters waves is about twice the average intensity of the shorter waves, which may mean that G-M waves tend naturally to be more intense than B-K waves.

(3) In accordance with the results expressed by the formula of Hollmann, the wavelength does definitely decrease at higher oscillating currents.

(4) Plate current and 'oscillation intensity' as expressed by the thermo-couple in the bridge seem to bear an exactly opposite relation to that usually assumed. Oscillation intensity maxima occur for the minima of the plate current curves. Where the bridge is not governing the wavelength of the oscillations, this may be explained by the loading effect of the bridge. When the bridge is at a loop of the standing waves on the wires, the current through it tends to be a maximum. At the same time it is placing the heaviest load on the oscillator, and the oscillation magnitude, as indicated by the plate current, falls. When the bridge is at a node, it places minimum load on the oscillator, the current through it is small, and the plate current rises, indicating actual greater intensity of the oscillations.

If the bridge were always the effective end of the oscillating circuit,it would be always at the same position on the standing wave,and the variation of current through it would correspond to the true variation of oscillation intensity.

The important general conclusion to be drawn from these curves and those first taken at a fixed position of the bridge is the possibility of obtaining meaningless characteristics from an oscillator when an over-all characteristic is not determined. When curves of the type of Fig. 52 are taken for different plate voltages,in addition to the quantitative changes,the oscillation peaks for the higher wavelength shift to one side or the other a distance of a few centimeters.

Thus when the first experimental curve was taken with the bridge at position 119 centimeters,the discontinuities found were due not primarily to the plate voltage change, but to the shift of the wavelength characteristic. For the case of zero voltage shown,the 119 centimeter position happens to be in the center of a region of 83 centimeter oscillation. At a positive plate voltage of about 5 volts, this region shiftf entirely past the 119 centimeter position, leaving 50 centimeter waves there. Hence the error that might have led to an untrue explanation.

Following this work,a few tests were made on the general method of obtaining electron oscillations by secondary emission, after the method of Gill and Morrell. Using the same circuit as that used for the work of the last few pages,with a thermo-couple bridge fixed at the end of 125 centimeters of external circuit, and with two rectifier power supplies giving the plate and grid potentials, readings of plate current, grid current and oscillation current were taken for continuously varying plate voltages from 300 volts to 0, atvgrid voltages in 25 volt steps from 350 to 150 volts. No wavelengths were measured.

The resulting characteristic as a working diagram, which does not indicate the intensity of oscillation is shown in Fig. 53. For plate voltages greater than the approximate line ab, up to the high plate voltage limit of oscillation in each case, the static characteristic of the tube is a falling one. Thus secondary emission is definitely taking place. The plate voltage does not become negative for any of the points considered.

To the left of the line ab oscillations are indicated as occurring for all grid voltage between 150 and 300 volts. These oscillations are due to the normal action of an electron oscillator. Hence below a certain grid voltage the change from the ordinary iscillations to those produced by secondary emission is continuous.

This particular diagram is a very useful one for showing the relation between the experimental work of different workers who have been dealt with in the historical summary. The section described immediately above indicates the nature of the work of Gill and Morrell in their second paper. To the left of the zero plate voltage axis, we can ascribe the researches of Pierret and Scheibe showing oscillations at high negative plate voltages. The region immediately around the zero plate voltage line for grid voltages from possibly 10 volts up,and for plate voltages from -10 to the line ab is the region in which the majority of all work has been done. And finally,for small positive or negative grid voltages, with plate voltages above some value,there is defined the region over which regenerative oscillations are obtainable. These regenerative oscillations in the present work at low grid voltages,and the limits of the region for the particular tube and external circuit used were determined as shown.

6. The result of testing different tubes.

Many writers have declared that they have found it impossible to generate electron oscillations with tubes having oxide filaments,but no difficulty was encountered in the present work in obtaining quite satisfactory osdillations from the UY227 triode and the UY224 tetrode tubes. The few tests made showed that these oscillations did not occur, however,until the emission current reached a value of about 75 to 100 milliamperes. Obviously continuous experimenting under such conditions is impossible.

The filaments of these heater-type tubes require several seconds to cool below the emission temperature. This accounts for a rather pretty phenomenon. If the filament voltage be removed when the tube is oscillating and the emission is at a high point,the very gradual decrease in the emission allows the plate current meter to follow the oscillation intensity at all points. A visual characteristic curve is obtained in a few

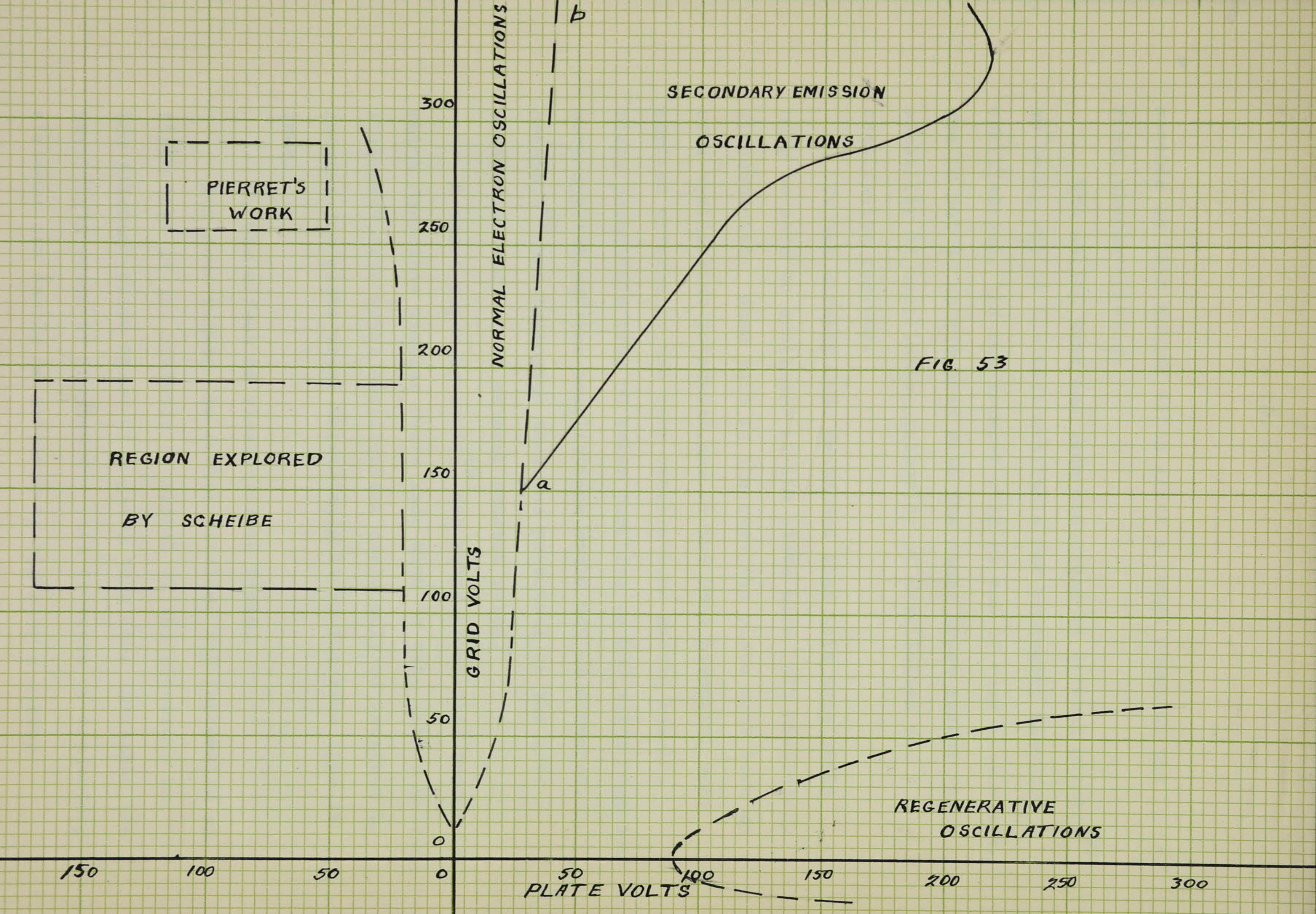

NORMAL ELECTRON OSCILLATIONS
b
SECONDARY EMISSION
OSCILLATIONS
PIERRET'S
WORK
REGION EXPLORED
BY SCHEIBE
a
GRID VOLTS
300
250
200
150
100
50
0
REGENERATIVE
OSCILLATIONS
150
100
50
0
50
100
150
200
250
300
PLATE VOLTS

FIG. 53

seconds by this method, which gives a rough check on the final characteristic.

The CG1162 tube has been described by several authors[67] as being one of the best available for producing electron oscillations. In the present work it was of very little use, and is not to be compared with the other types tested for stability of oscillation, intensity of oscillation and oscillation regions.

It has already been mentioned that this tube could only be made to oscillate if the plate were left absolutely disconnected. When this is the case, the plate must take up some equilibrium potential, and if the same potential were applied externally, the same oscillations should result. Plate potentials from 50 volts positive to 600 volts negative were applied, but the oscillations could not be detected. Beauvais[68] has indicated that the potential of the free electrode tends to be several hundred volts.

A short paper by Breit[69] was found after this test, which describes similar tests made with "a tube with a helical filament", from which oscillations could only be obtained by leaving the plate free. Undoubtedly it is the same type of tube.

7. The effect of electrostatic field.

For some reason the author obtained the impression at first that if the distance of travel of the electrons in the filament-plate space of a given tube were increased, the wavelength would be increased. This increase of trajectory distance can easily be obtained by applying a strong electrostatic field along the axis of the filament.

Using the arrangement of Fig. 54, an attempt was made to produce this result. By connecting three rectifiers in series, a potential of about 3500 volts was obtained, and applied across the two copper plates shown, which are perpendicular to the axis of the filament, and are about 4 centimeters apart. This means an electric field of over 800 volts per inch. In the tube itself oscillations were being maintained at 15 volts grid voltage. The grid-filament distance of .225 centimeters indicates the field strength to be about 175 volts per inch. Calculation of the diagonal trajectory of the electron in the tube in this case showed

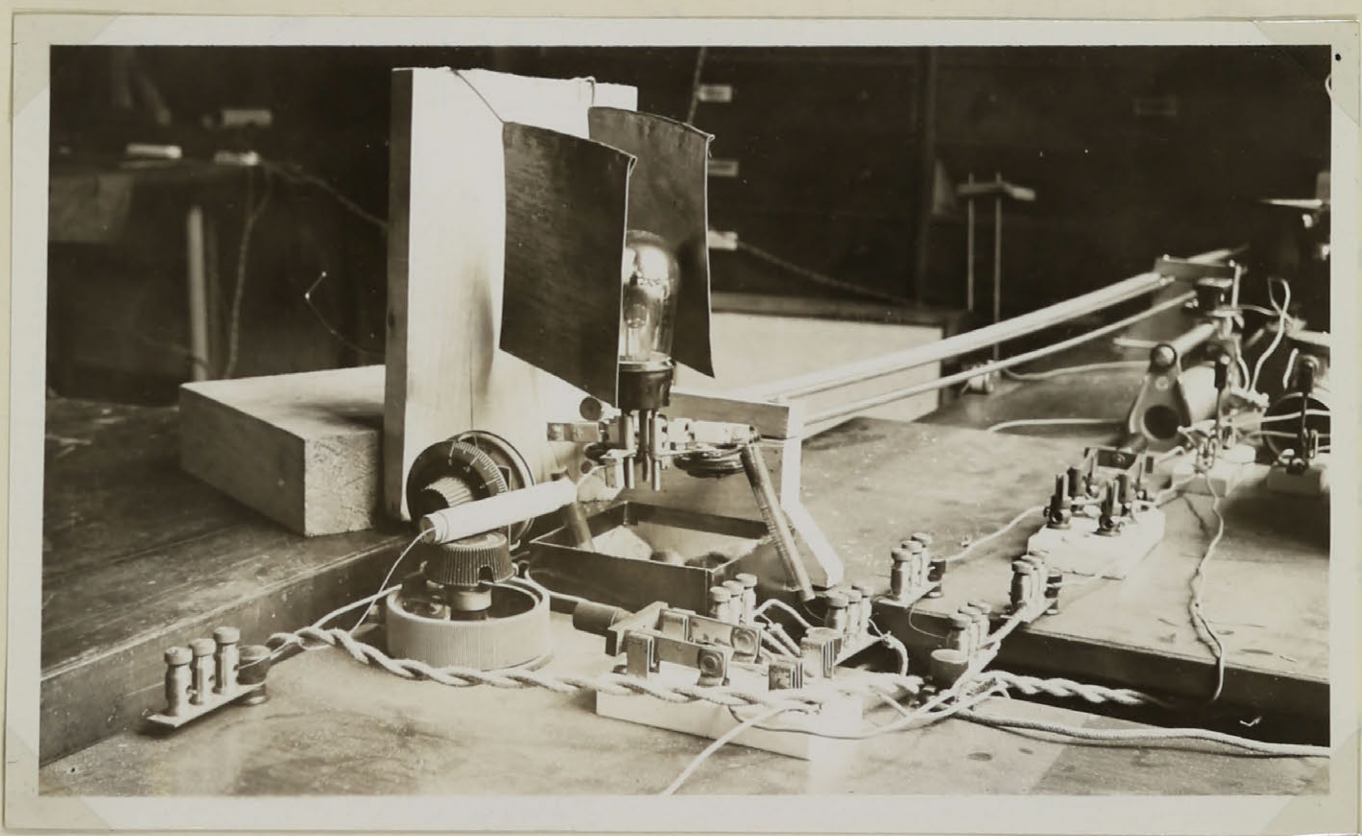


Fig. 54

that a wavelength shift of about 50%, or more, was possible.

On applying the field neither oscillation intensity nor wavelength changed observably. The plate current was visibly reduced, indicating that a fraction of the electrons are being deflected to the walls of the tube at one end of the filament.

Theoretical consideration of the problem suggests at once that the original assumption was a fallacy. The wavelength of the electron oscillations is determined by the time taken to travel the path, not by the distance travelled. Since the radial velocity of the electrons is unchanged by the electrostatic field, and since also the radial distance they cover during an oscillation is unchanged, the electrostatic field should apparently have no effect on the wavelength. The test is at least a thorough experimental verification of this result.

Another line of investigation is suggested by the curious phenomena which occur when the charged condensers of the rectifiers used are discharged by short-circuiting the plates. This of course causes a very rapid variation of an electric field from the initial value to zero, which in turn produces a magnetic field. Oscillations in the two fields take place at some resonant frequency. The effect on the operation of the tube was to immediately reduce the oscillation intensity to zero, then to keep it at a low value for possibly two seconds, then to allow it to build up gradually over a period of 4 or 5 seconds. The implied field of investigation is the effect of high frequency or even continuous magnetic fields on the operation of the oscillator. The continuous field effect has already been considered to some extent by Hollmann. [34]

8. The principal experimental work.

The final object of this experimental work has been defined as the determination of enough space model characteristics for one or more vacuum tubes to indicate their complete oscillation possibilities. The amount of work required for such a problem has also been suggested. The natural result has been only a partial attainment of the initial aims. Nevertheless the results are sufficient to indicate the potentialities of the method.

The characteristics all through have been obtained with the circuit shown exactly by Fig.38, with the external Lecher system the only constructional variable. Three conditions have been tested:

(1) Using no external circuit.

(2) Using an external circuit of 135 centimeters length.

(3) Using an external circuit 240.4 centimeters in length.

Each of the last two circuits has been constructed of the $\frac{1}{4}$" brass rod mentioned previously, and has been terminated by a flat copper strip soldered to the rods.

The procedure for obtaining the curves is as follows: Starting at zero grid voltage, the filament current is adjusted to a low value. The grid voltage is raised slowly and continuously until a sudden rise of plate current indicates the presence of oscillations. If no oscillations are found for the filament current shown, a higher value is used and the process is repeated until they are detected. When a region is encountered, grid voltage is varied in very small steps across it, grid current, plate current and wavelength being recorded at each grid voltage value. The grid voltage is then increased slowly until the next oscillation region is encountered,where the same readings are taken.

Plate voltage is maintained at zero with respect to the negative filament terminal throughout. Filament current is maintained constant within 1 milliampere for each curve,although the numerical value given for each curve undoubtedly has not this precision. The intensity of oscillations at each point is expressed as the rise in plate current caused by the oscillations. That is,the plate current is read with the oscillations stopped and then with the oscillations present. The difference is taken as the intensity measure.

The wavelengths have been measured in all cases with the small absorption wavemeters. The fact to which attention was called on page 119 that no plate current kick can be observed under certain conditions is not an experimental problem. All tests indicated that the wavelength varies only slightly across any one region of oscillation,and since a region is always in an unstable state before it reaches the stable condition,its wavelength can always be determined before stability exists. No valuable information is lost by omitting wavelength measurements in the very few cases where the wavemeters cannot be used.

The curves first obtained in this way,with no external circuit connected to the tube,are given by Fig. 55.

FIG. 55

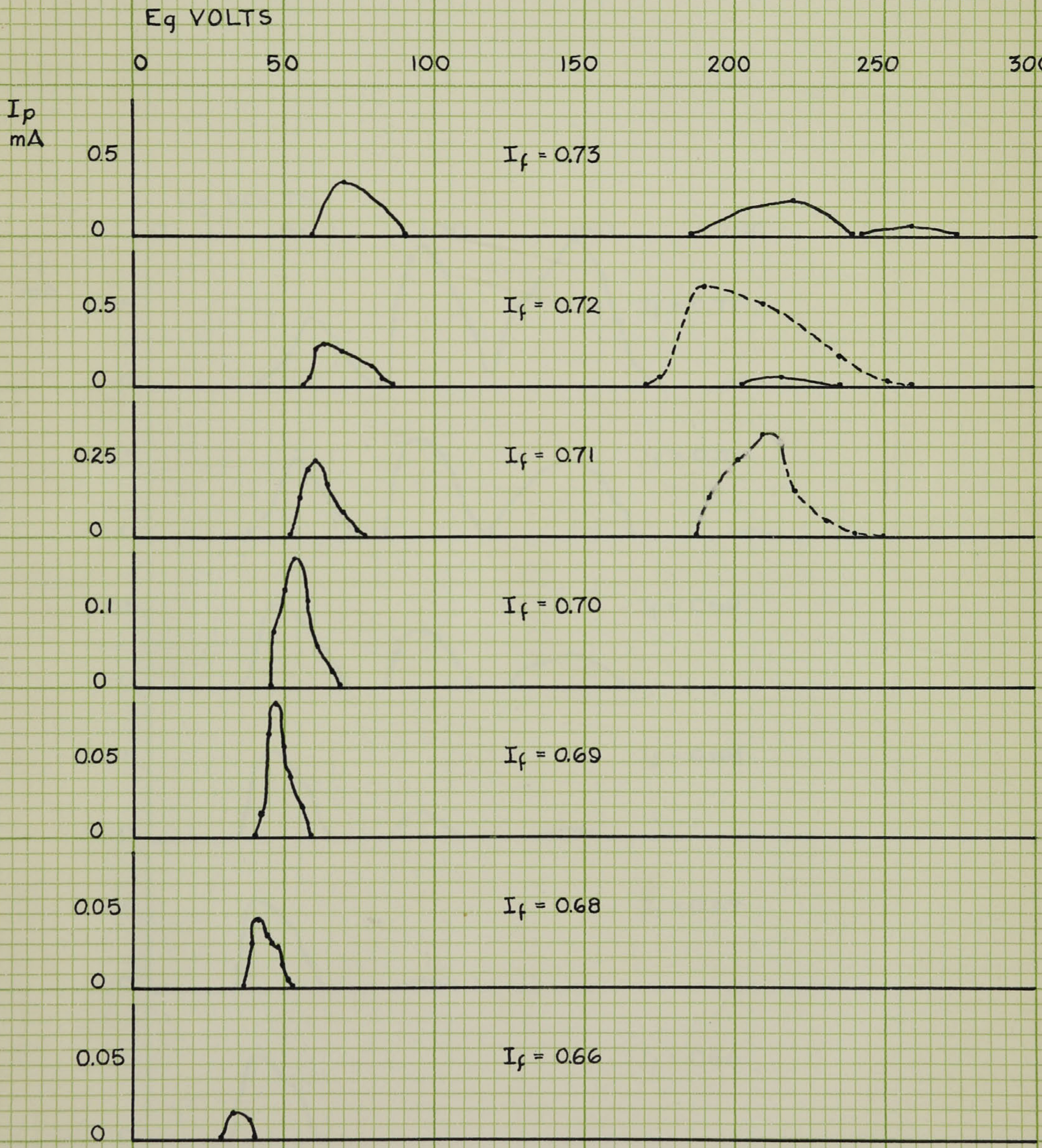

Eg VOLTS
0
50
100
150
200
250
300
Ip mA
0.5
0
I_f = 0.73
0.5
0
I_f = 0.72
0.25
0
I_f = 0.71
0.1
0
I_f = 0.70
0.05
0
I_f = 0.69
0.05
0
I_f = 0.68
0.05
0
I_f = 0.66

Fig. 56

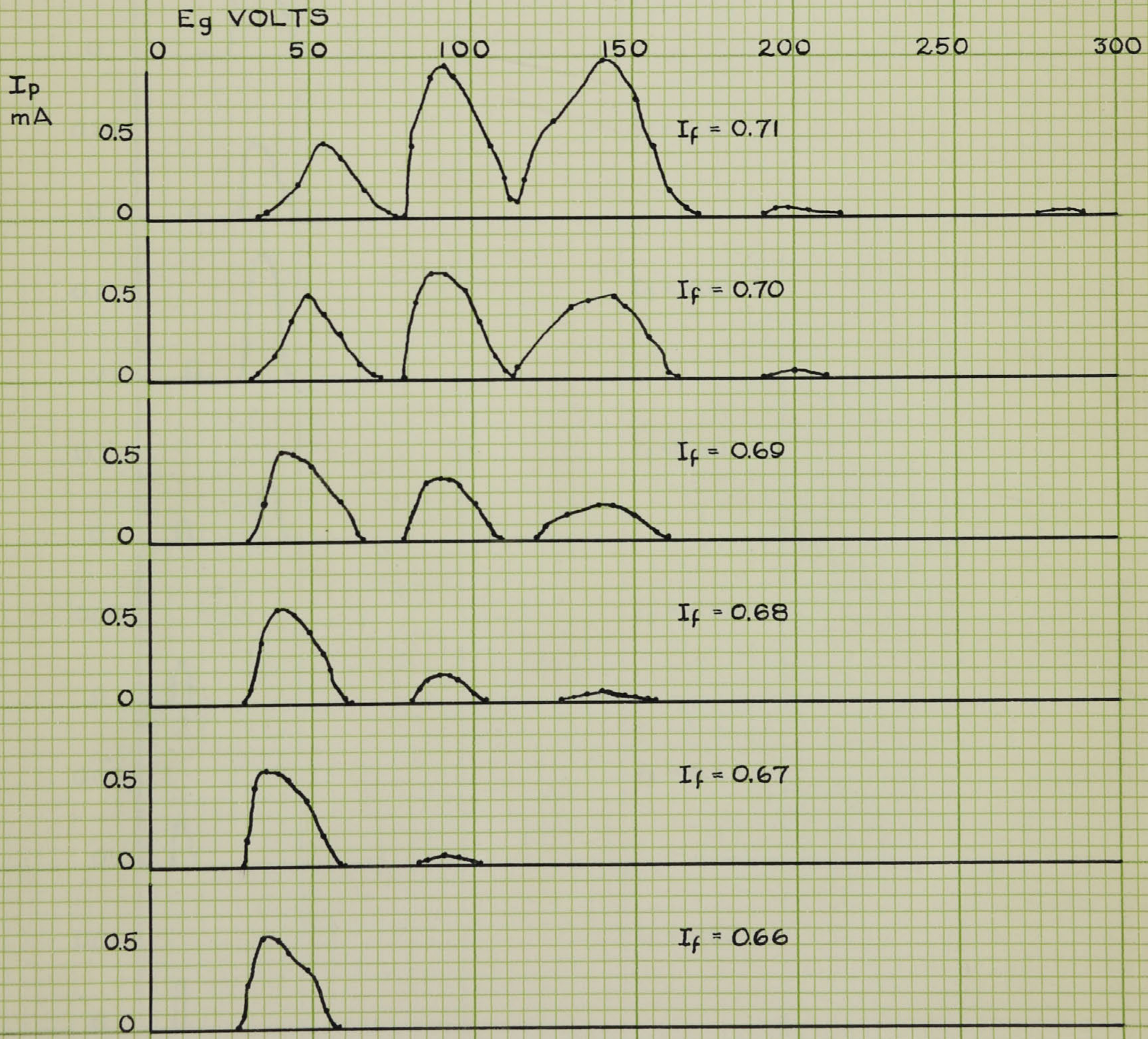

Eg VOLTS
0
50
100
150
200
250
300
Ip
mA
0.5
0
If = 0.71
If = 0.70
If = 0.69
If = 0.68
If = 0.67
If = 0.66

Fig. 56 (contd)

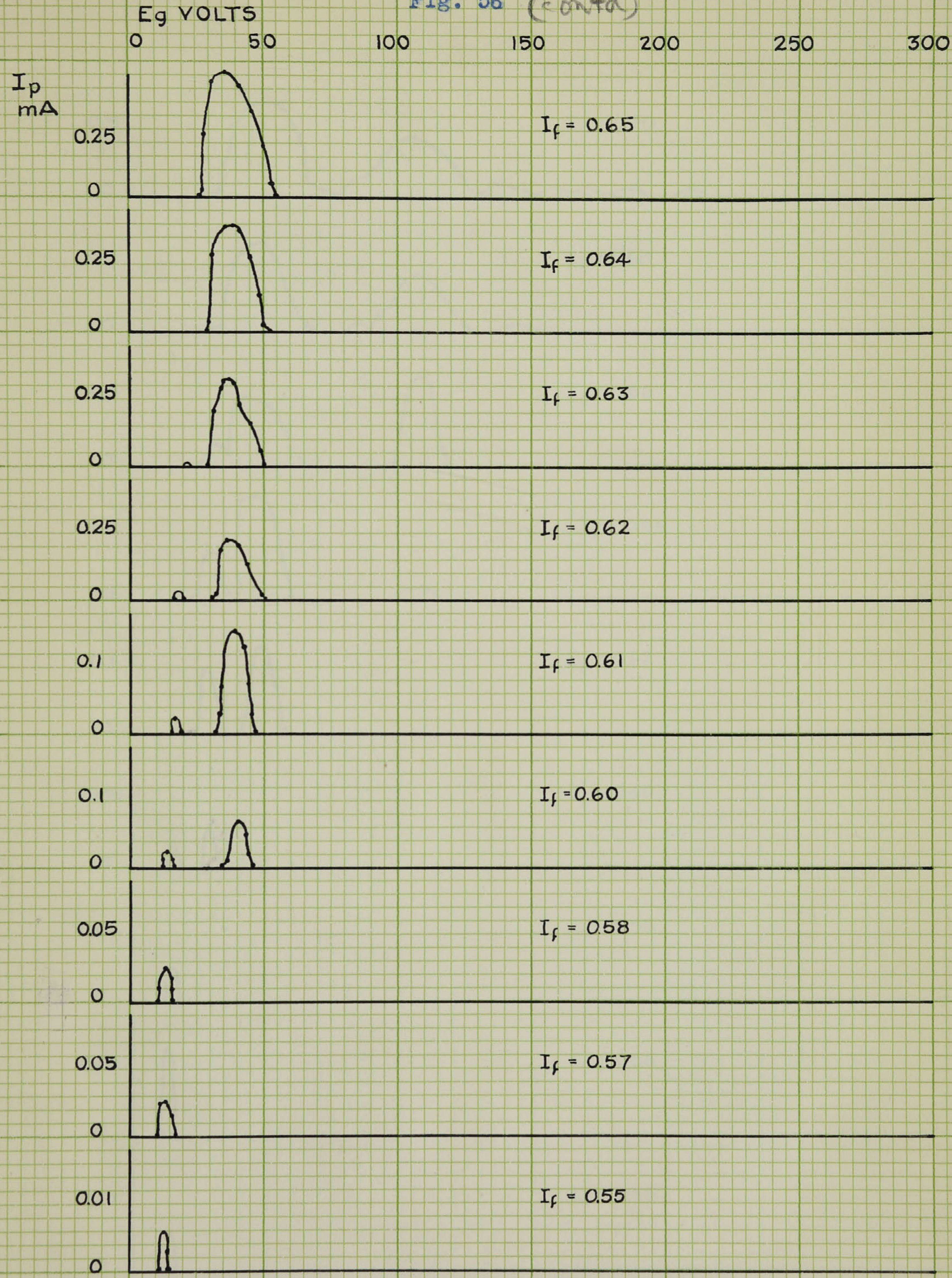
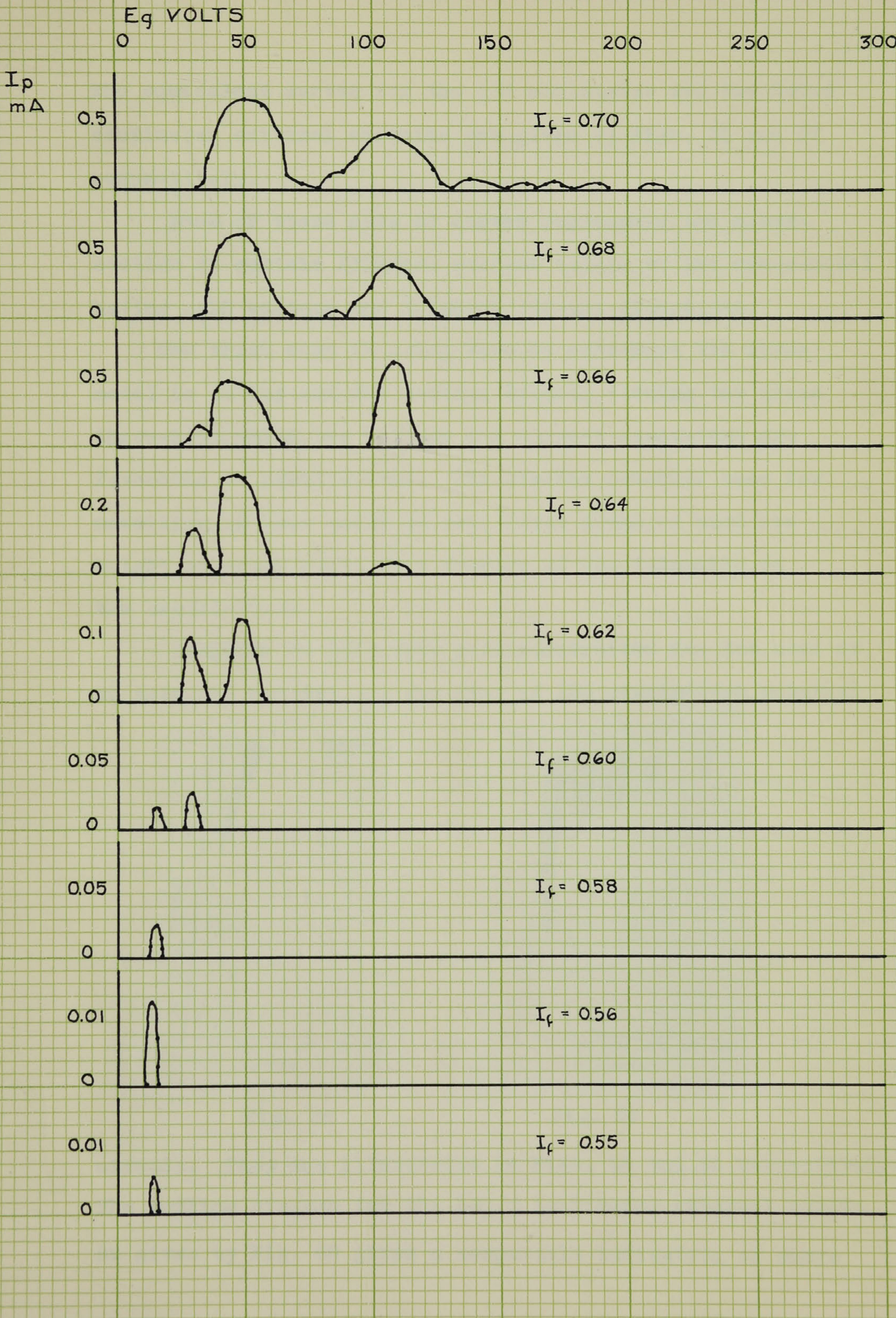

Eg VOLTS
0
50
100
150
200
250
300
Ip
mA
0.25
0
I_f = 0.65
0.25
0
I_f = 0.64
0.25
0
I_f = 0.63
0.25
0
I_f = 0.62
0.1
0
I_f = 0.61
0.1
0
I_f = 0.60
0.05
0
I_f = 0.58
0.05
0
I_f = 0.57
0.01
0
I_f = 0.55

Fig. 57



Eg VOLTS
0
50
100
150
200
250
300
Ip mA
0.5
0
If = 0.70
0.5
0
If = 0.68
0.5
0
If = 0.66
0.2
0
If = 0.64
0.1
0
If = 0.62
0.05
0
If = 0.60
0.05
0
If = 0.58
0.01
0
If = 0.56
0.01
0
If = 0.55

The equivalent curves for the 135 centimeter and the 240.4 centimeter external circuits are given by Figs. 56 and 57 respectively.

Each of these sets of curves represents the cross-section at certain filament current values of the space-model having grid voltage and filament current dimensions.

The first step in using them to construct the space model is to lay out the working diagram, showing the areas throughout which the voltage and current conditions are favorable to oscillations. The plastic material used for modelling is then built up over these areas, so that its height at every point is a measure of the intensity of the oscillations.

Diagrams of this type were constructed for the case of no external circuit and the case of 135 centimeters external

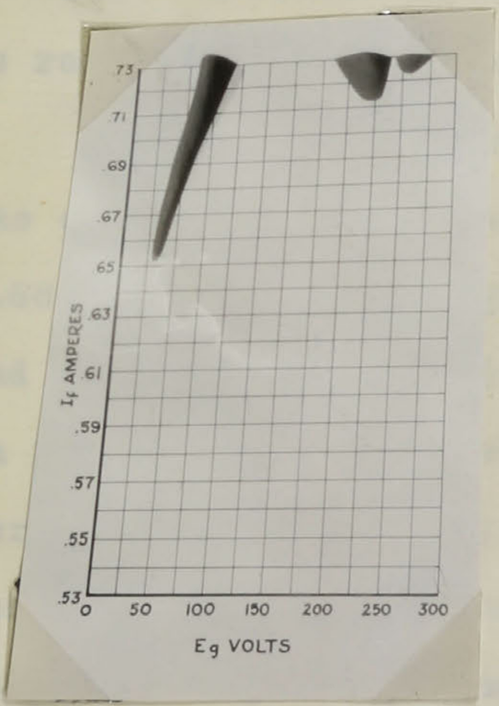


Fig. 58

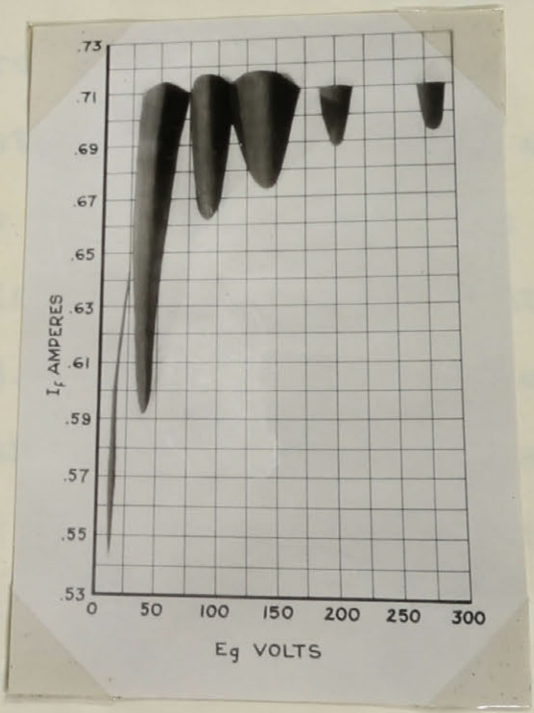


Fig. 59

circuit. They are illustrated in Figs. 58 and 59 respectively. The working diagram for the 240.4 centimeter external system, as given by Fig. 60 gives a comparable indication of where the oscillation regions exist in this case, but does not show relative intensities for the different regions.

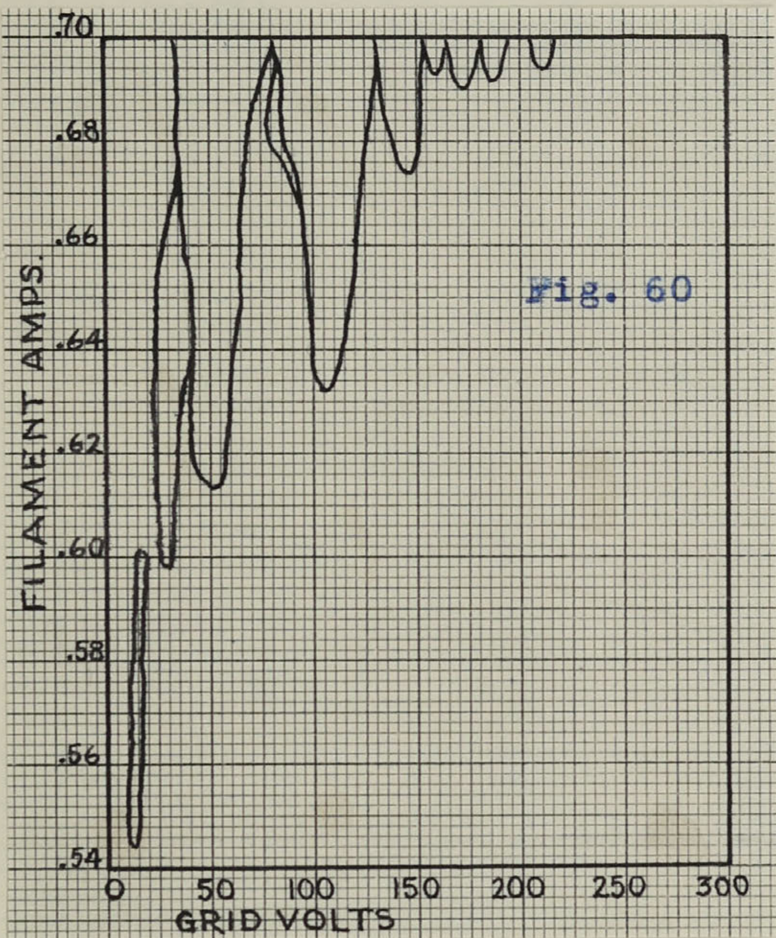


Fig. 60

The additional curves of Figs. 61,62, 63, are necessary for discussional consideration of the space models.

Fig. 61 illustrates the grid current saturation curves of the tube used, taken with the plate at the same potential as the filament.

Fig.62 shows a peculiar variation of the plate current as the grid voltage is raised gradually from zero.

Fig. 63 is the complete characteristic for each of the external circuits at the one value of filament current, 0.68 amperes. Wavelength, plate current as oscillation intensity, and grid current are plotted. Since the space model does not in itself consider wavelength, curves such as this are necessary for a thorough exposition of a tube's characteristic. These complete characteristics were taken for each of the individual curves of Figs. 55,56 and 57, but they can be discussed without their being presented in full.

The work so far is not sufficiently complete to warrant any detailed theoretical conclusions. The only discussion that

FIG. 62

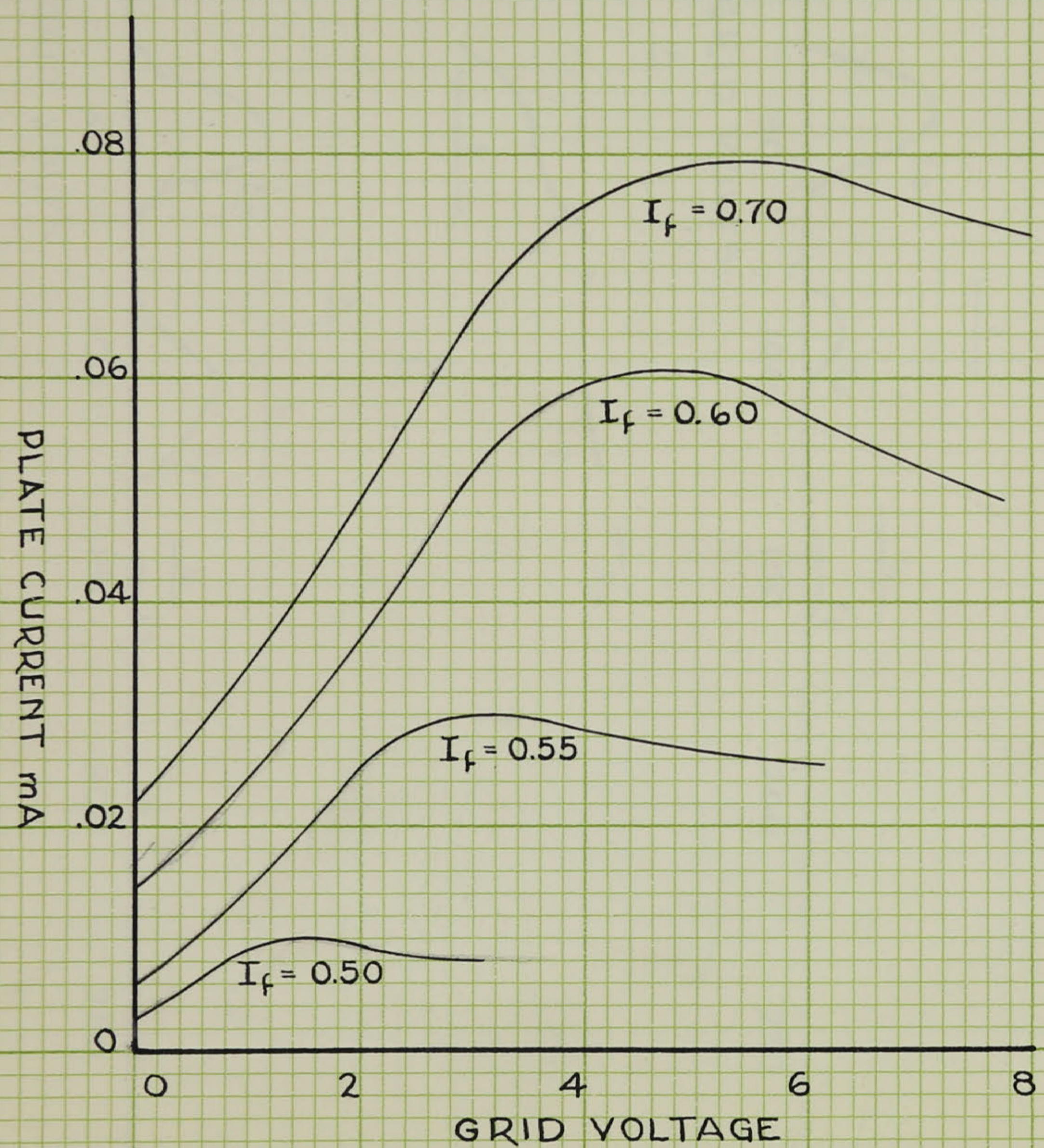


PLATE CURRENT mA
.08
.06
.04
.02
0
0
2
4
6
8
GRID VOLTAGE
I_f = 0.70
I_f = 0.60
I_f = 0.55
I_f = 0.50

FIG. 61

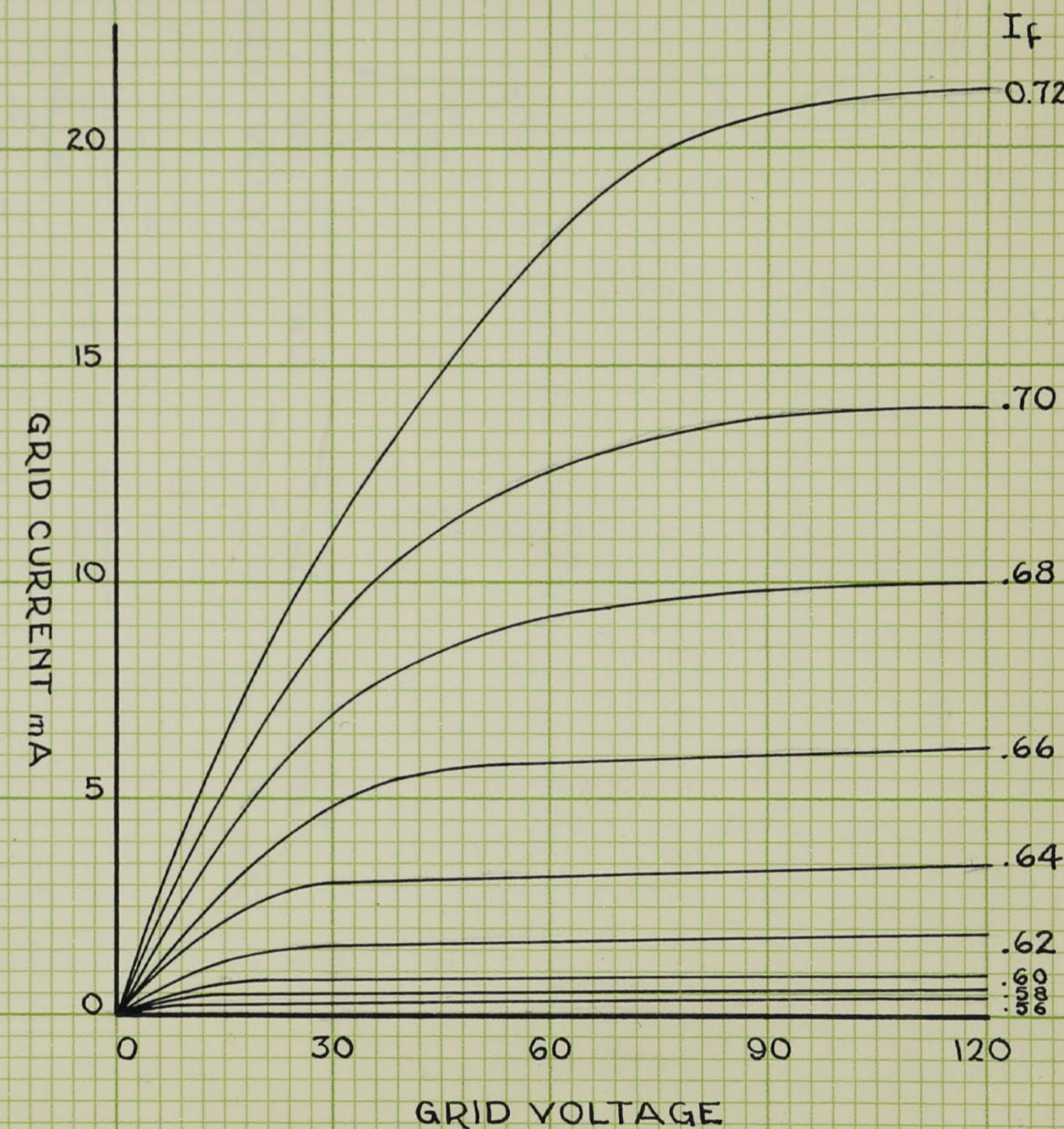
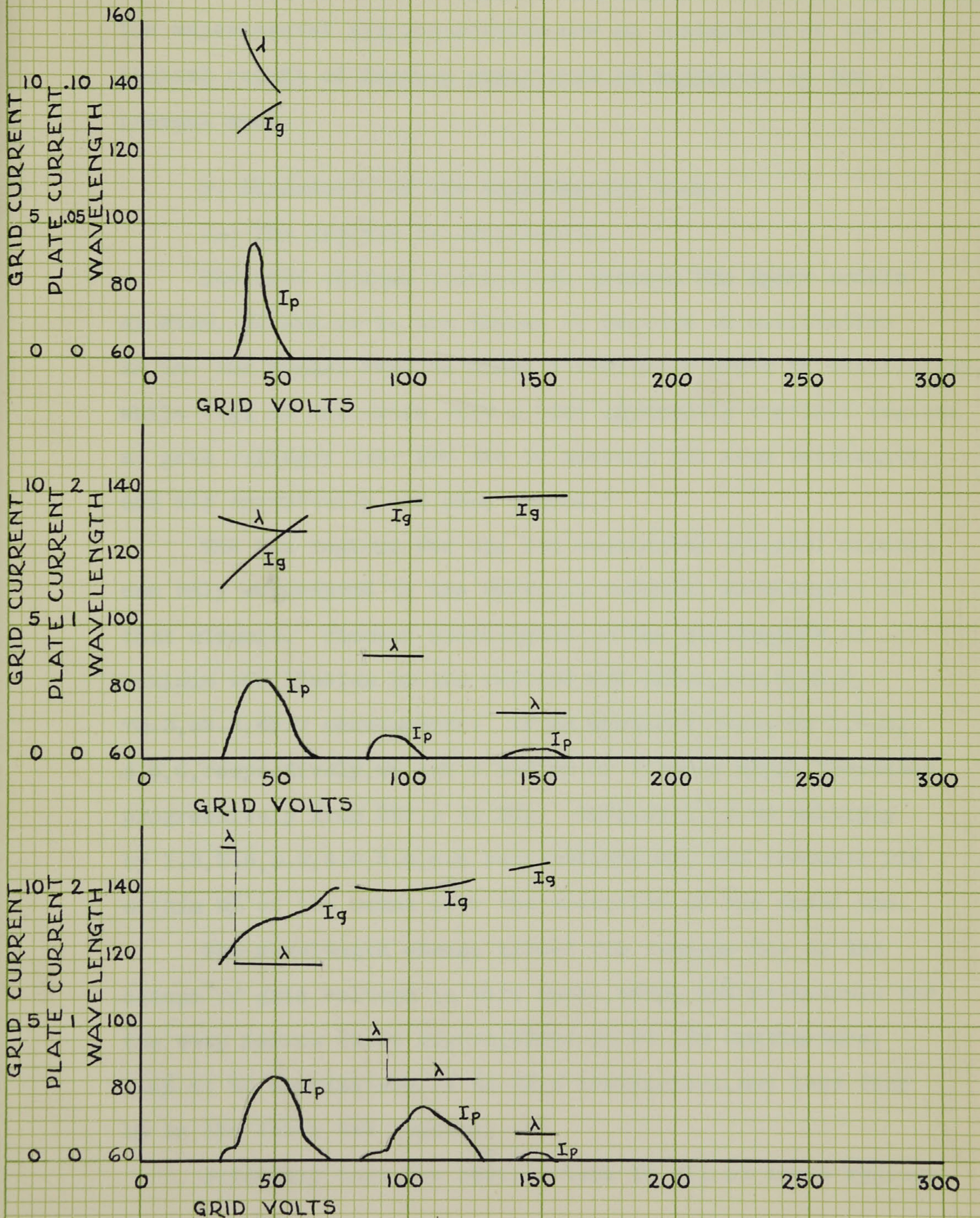

GRID CURRENT mA
20
15
10
5
0
0
30
60
90
120
GRID VOLTAGE
I_f
0.72
.70
.68
.66
.64
.62
.60
.58
.56

Fig. 63


GRID CURRENT
PLATE CURRENT
WAVELENGTH
160
10 .10 140
120
5 .05 100
80
0 0 60
λ
Ig
Ip
0
50
100
150
200
250
300
GRID VOLTS
10 2 140
120
5 1 100
80
0 0 60
λ
Ig
Ip
GRID VOLTS
GRID VOLTS

can be sincerely presented is an attempted interpretation of the experimental characteristics, and an indication of the logical result of further experiment as suggested by the present work.

9. Discussion of the experimental work.

(a) The regions of oscillation.

The most obvious distinction between the space models of Figs. 58 and 59 is the number of regions of oscillation in the two cases. Fig. 59 shows 6 different modes of oscillation, while Fig. 58 indicates only 2.(The apparently distinct regions at grid voltages over 200 are of exactly the same wavelength, and are essentially the same region.)

The six regions for the 135 centimeter external circuit can only correspond to the harmonic resonant wavelengths of that circuit. Themean wavelengths or the wavelengths of maximum oscillation in the regions are 227.5,133.0,91.0, 73.3,59.8,46.0 centimeters. If we multiply these by 1,2,3, 4,5,6,respectively,we get a series of figures which increases progressively from 227.5 to 302. Curiously,if we multiply by 1.5,2.5,3.5,4.5,5.5,6.5 respectively,all the products lie within 2% of the means with the exception of the final one.

The wavelength change across the regions due to the change of grid voltage is very small,being not noticeable for the very narrow first region,about 5% at 133 centimeters, 1.5% at 90 centimeters,1% at 73.3 centimeters,and less than 1% in the other two regions.

Evidently then,the oscillations in all of these regions are 'controlled oscillations',or what have come to be known as Gill-Morrell oscillations.

Where no external circuit is used,the oscillation region at the low grid voltages shows wavelengths all the way from 170 centimeters to 109 centimeters,according to grid voltage. For the oscillations at high grid voltage,the wavelength remains almost perfectly constant at 56.0 centimeters,regardless of grid voltage.

If the B-K product of the grid voltage and the square of the wavelength is calculated for all wavelengths in the first region,regardless of filament current,the value is found to be constant within a small fraction of 1%. Evidently,then, this region consists of natural oscillations,not controlled by any resonant circuit. The second region at 56 centimeters must be a controlled region,due to some resonant circuit in the tube itself,or in the leads to the tube.

For the 240 centimeter external circuit,there are also six regions of oscillation in which the wavelength can be measured. Those shown for high grid voltages at 0.70 amperes heating current are too weak to allow the wavelength to be measured.

The wavelengths at maximum intensity in the six regions are 216.5,157.6,119.0,96.2,83.5,69.0 centimeters. Multiplying by 2,3,4,5,6,7 respectively,and omitting the first,all the products lie within 2.5% of the mean.

Evidently,then,these again are purely controlled oscillations,and the resonant wavelengths are almost exactly the harmonics of a 240 centimeter Lecher circuit.

It is observable in both of these cases, that on multiplying the decreasing wavelengths by the increasing order of harmonic, the resulting product shows an increase with the order of the harmonic. Tests must be made on more Lecher circuit lengths before this can be considered a typical characteristic.

From Fig. 62, the wavelength range across a region centering around 45 volts decreases progressivly. With no external circuit it is 19 centimeters; with 135 centimeters external circuit it is 4.7 centimeters; with 240 centimeters external circuit it is 1.0 centimeters. The generalization indicated by these results is that the higher the harmonic order of a given region, the more rigidly is its wavelength controlled by the external circuit.

This suggests the question as to whther or not there can be degrees of control of the wavelength. The alternative would be that only pure G-M or pure B-K oscillations should exist. If this alternative were the actual case, there would be a firm foundation for the distinction between the two types of oscillation. If there can be degrees of control, we must discard the conception of two individual types of oscillation, and admit that an oscillator tends always to produce natural frequency electron oscillations. In the presence of an external circuit having a sufficiently high ratio of inductance to resistance (i.e. high Q) the wavelength changes in the direction of the resonant wavelength of the circuit. The degree of change, or the extent to which the circuit controls the wavelength will be determined by the magnitude of its Q.

Although this theory has apparently never been expressed before in so many words, Potapenko's most recent paper [54] suggests that his present opinions are along this line. Kapzov [70] has indeed been able to show wavelength curves having slopes varying from that of the B-K curve to a horizontal line over a definite range of grid voltage, merely by using different types of external circuit.

(b) The shortest and the longest waves.

Considering the space model of Fig. 59 in its entirety, there are several interesting features with regard to the limitations of the oscillator.

If we draw a line through the minimum filament current points of each of the regions of oscillation, we get a curve which has the general shape of a saturation curve. If we refer this curve to the saturation curve of the tube, Fig. 61, very little imagination is required to observe that this derived curve, considered with respect to the coordinates on the base of the space model, represents at each filament current the value of grid voltage which JUST produces saturation. It might be defined as the locus of the points at which the derivative of the mutual conductance of the tube approaches zero, or at which the mutual conductance itself approaches zero.

Then since all the oscillation regions lie at much higher filament currents and only slightly higher grid voltages than the points determining this curve,it is obvious that all oscillations must be occurring for a degree of saturation at least less than is represented by these points. Consequently they must be occurring only for points at which the mutual conductance of the tube is greater than zero, and it would appear that they can never occur when complete saturation has set in.

The oscillation region at low voltage of Fig. 58 is definitely inclined to the filament current axis at a greater angle than is the case for any of the regions of Fig. 59. The reasoning of the last paragraph would suggest that the angle of inclination must always be less than such a value as would allow the region to cut the derived curve. Large values of the inclination angle can therefore occur only at high values of the filament current.

Since oscillations do not exist,then,for saturation beyond a certain limit,it is apparent that very high grid voltages can only produce oscillations when the filament current is such that the grid voltage in question does not produce complete saturation. If very short waves are to be obtained by increasing the grid voltage,therefore,the emission at the same time must be increased. Increase of either of these factors tends to increase the power dissipation of the grid of the tube. Consequently the short wave limit that can be reached in this way is determined by the heat dissipation ability of the electrodes.

Considering the high wavelength region of Fig. 59, it appears that these oscillations die out at a filament current of about 0.64 amperes, after having passed through a maximum value at 0.60 amperes. It would appear from this that oscillations also become impossible when the mutual conductance of the tube has too high a value. The curves of Fig. 56 show that the second oscillation region of Fig. 59 is beginning to decrease in intensity for filament currents greater than 0.70 amperes, which supports the above view.

Thus oscillations can occur in general only at points where the mutual conductance of the tube lies between two definite limits. This does not account for the existence of regions of oscillation, but merely defines the area in which such regions can be found.

To obtain the longest possible waves with an oscillator, the above limitations require that the filament current be very low, so that saturation sets in at a low grid voltage. With the 135 centimeter external circuit, the fundamental wave of 227 centimeters was found. With the 240 centimeter external circuit, however, the fundamental wave, which should be from 400 to 500 centimeters wavelength could not be obtained, even at emission currents of a few micro-amperes.

The curves of Fig. 62 have been obtained to illustrate a possible limitation on the generation of long waves at low grid voltages. On increasing the grid voltage from zero, the plate current rises to a maximum value for a low grid voltage, and then decreases. It is suggested that this is due to the initial velocity of the electrons leaving the filament, and that this same influence prevents the generation of long waves. At low grid voltage, the voltage of initial velocity is appreciable relative to the grid voltage. When the electrons pass the grid with velocity due to the grid potential, their initial velocity is sufficient to carry them to the plate, if the grid field does not exceed some certain value. At low grid voltages all the electrons that pass through the grid will reach the plate, and oscillations are made impossible. It is probable that a wavelength of about 300 centimeters is the maximum obtainable with the tubes used.

Such, in the main, are the experimental results that have been obtained in the present work, and the mechanical theories that arise from them. Some of the work is of interest in itself, while a great deal of it is more important because of the new avenues of experimental work it suggests. It is very probable that the writer will continue this work along some of the lines indicated.

3. Subjects for future experiment.

The principal experimental work suggested is the continuation of development of the space-model method for the presentation of oscillation characteristics of a tube. In this work, for example, it was suggested on page 145 that a given oscillation may be more stable the higher its harmonic order in relation to the external circuit of the oscillator. But the space-model method had not been applied widely enough to verify this in the general case.

The suggested relation between the saturation curves and the possibility of oscillation should lend itself to mathematical treatment.

Although we have explanations for the reason of existence of regions of oscillation,we have not even a qualitative explanation of the factors which determine the orientation of these regions on working diagrams. A study of Fig. 59 and the curves of Fig. 56 from which it is constructed indicates definitely that with the tube used for these tests,it would be impossible to demonstrate two regions of oscillation on varying the filament current continuously. None of the regions oger-lap on a projection on the grid voltage axis. But in a number of cases such regions have been demonstrated,and there must be determining factors in this connection. They can only be investigated by the method of working diagrams or space models.

The problem of transition states between B-K and so-called G-M oscillations is one that is far from being satisfactorily settled. Investigations of this can be carried out using simply two dimension characteristics, for bridges of different mechanical constructions and electrical constants.

If tube construction equipment is available,a practically untouched field of research is opened up. Otherwise,significant information may often be obtained by comparison of results for available types of tubes.

Research on the effect of gas in tubes is not considered as pertaining truly to the subject of electron oscillations. Rather it is part of the much broader field of high frequency gaseous phenomena.

Appendix

1. Kapzov-Gwosdower tabulations of f(x) and g(x).

x	f(x)	difference
1.70	.63336	.00434
1.75	.62902	.00483
1.80	.62419	.00516
1.85	.61903	.00537
1.90	.61366	.00548
1.95	.60818	.00549

x	f(x)	difference
2.00	.60269	.00543
2.05	.59726	.00530
2.10	.59196	.00512
2.15	.58685	.00491
2.20	.58193	

x	g(x)	difference
.82	1.07310	.03953
.83	1.11263	.04084
.84	1.15347	.04219
.85	1.19666	.04361
.86.	1.23937	.04506
.87	1.28433	.04658
.88	1.33091	.04814
.89	1.37905	.04976
.90	1.42881	.05144
.91	1.48025	.05319
.92	1.53344	.05500
.93	1.58844	.05688
.94	1.64532	.05882
.95	1.70414	.06084
.96	1.76498	.06293
.97	1.82791	.06510
.98	1.89301	.06737

x	g(x)	difference
.99	1.96038	.06970
1.00	2.03008	.07213
1.01	2.10221	.07466
1.02	2.17687	.07727
1.03	2.25414	.08000
1.04	2.33414	.08283
1.05	2.41697	.08576
1.06	2.50273	.08881
1.07	2.59154	.09199
1.08	2.68353	.09528
1.09	2.77881	.09871
1.10	2.87753	.10227
1.11	2.97979	.10597
1.12	3.08576	.10982
1.13	3.19558	.11383
1.14	3.30941	.11799
1.15	3.42740	

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