INVESTIGATIONS IN THE FIELD OF ULTRA-SHORT ELECTROMAGNETIC WAVES

Thesis by

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SYNOPSIS

The production of ultra-short electromagnetic waves by the retarding field method is analysed. It is found that to generate oscillations of very short wave lengths, it is more effective to reduce the size of the electrodes of the vacuum tube and to design the tubes to oscillate higher orders than to increase the grid potential.

Experiments were made with the Pliotron FP-126 tubes as retarding field oscillators. These tubes generated strong normal and higher order oscillations. The wave length of the normal oscillations differed considerably from the values calculated from the Barkhausen and Scheibe equations. For the higher order oscillations, the observed wave lengths were approximately equal to values calculated according to Potapenko's formula: $n^2\lambda^2E_g = C$. It was found that the predominating higher order oscillations were generated by the grid coil at its natural frequency. Its wave length agrees with that calculated from its dimensions.

Tubes with plate diameters as small as 0.05 cm. were made. They generated normal as well as higher order oscillations. They were designed so that the grid had a natural wave length of about 1 cm. The grid potentials calculated agree fairly well with the values observed. The energy of oscillations with these tubes was exceedingly small. The wave length of 1 cm. is about the shortest limit that can be obtained by the retarding field method.

INTRODUCTION

The generation of undamped electromagnetic waves of very short wave lengths can be achieved by three distinct methods with their respective merits and disadvantages. They are: 1) the Feed-Back type as is used in conventional oscillators of communication transmitters; 2) the Magnetron oscillator; and 3) the Retarding Field type oscillator. As the present work is concerned with the last type, the first two will be reviewed only very briefly.

Feed-Back Type Oscillator. In the feed-back type oscillator a thermionic vacuum tube of three or more electrodes is used. The principle of its operation is, as the name suggests, that part of the energy in the plate circuit is fed back to the grid circuit, and through the property of amplification of the vacuum tube, sustained oscillations are generated. The period of the oscillation is determined by the inductance and capacity of the circuits concerned. For frequencies up to 100 megacycles the circuit constants are of such magnitudes that the capacity between the electrodes and the inductance of their leads constitute only a small fraction of their total value. But as one tries to generate waves of higher and higher frequencies using such tubes, a limit is soon reached whereby the inductance of the leads of the electrodes and the capacity between them constitute the whole tuning circuit. In general, tubes cease to operate properly when the time it takes the electrons to travel from the filament to the anode becomes comparable with that of the period of oscillation. Under such circumstances the efficiency is usually very low. Using tubes of special design it is possible to generate waves of the order of 1000 megacycles (30 cm.) as an upper limit. The advantages of oscillators of this type are the simplicity of the circuits and ease of operation and comparatively high efficiency as a power converter. The obtainable efficiency at 1000 megacycles for tubes specially designed for this purpose is about ten per cent.

Magnetron Oscillator. In the generation of electromagnetic waves using a magnetron, the motion of the electrons is affected by both an electric and magnetic field. By using exceedingly intense electric and magnetic fields and electrodes of very small dimensions, it has been possible to generate waves of the order of one centimeter with measurable power (1). For such short wave lengths it necessitates a magnetic field of more than 10,000 gausses. Besides the inconvenience of requiring an extra magnetic field of intense strength, the constancy of the oscillations is usually very poor. But the high output at very short wave lengths is not excelled by the other two methods.

Retarding Field Oscillator. For the generation of oscillations by the retarding field method, thermionic vacuum tubes of three electrodes and of the concentric cylinder type are invariably used. The mode of operation is, however, different from the feed-back type. In the latter the plate is connected to a high positive potential and the grid to a slightly lower potential than that of the filament or cathode; while in the retarding field type of operation, the grid is connected to a high potential and the plate to the filament or to a slightly lower potential. The period of oscillation is about equal to the time for the electrons to travel from the filament to the plate and back to the filament again. Thus what is inherently a drawback in the feed-back type oscillator is utilized here. Within certain limits, by subjecting the electrons to a high accelerating electric field and by making the dimensions of the electrodes small, it is possible to decrease this time of flight of the electrons through the cycle to intervals which correspond to wave lengths of the same order of magnitude as obtainable with the magnetron.

Barkhausen and Kurz Oscillations. In experimenting with tubes having concentric cylindrical electrodes, Barkhausen and Kurz found accidentally the kind of oscillation now bearing their names (2). As mentioned above the grid is connected to a high potential while the plate is connected to nearly the filament potential. The wave length of the oscillation was found to depend on the voltages of the electrodes and to be independent of the attached circuit constants. The same authors furnished a simple explanation for the phenomenon. For simplicity of analysis, they assumed that the electrodes of the tube were infinite planes. Electrons after being emitted from the cathode plane are subjected to the accelerating field of the grid. A small portion of the electrons will be caught by the grid, and the majority will pass through it to the space between the plate and the grid. Here the electrons face a retarding field and will be repelled before they reach the plate. If they miss the grid again in the return trip, inertia will carry them to where they started, and the cycle repeats itself. The time of the cycle depends evidently on the accelerating field and the geometry of the electrodes. It is easy to show that the wave length corresponding to this period is

$$\lambda = \frac{1000}{\sqrt{E_g}} \frac{d_p E_g - d_g E_p}{E_g - E_p}$$

where E_g and E_p are the potentials of the grid and plate in volts respectively; d_g and d_p, their respective diameters in centimeters. When the plate is connected to the filament, then

$$\lambda^2 E_g = d_p^2 \cdot 10^6.$$

Crude as the explanation may seem, considering that the electrodes are far from being infinite planes in the actual case, Barkhausen and Kurz showed that there was a striking check between the experimental and calculated wave lengths.

It is evident that to maintain the oscillation it is necessary that the electrons gather themselves into groups and execute the cycle in phase. Just how this is effected was not understood by Barkhausen and Kurz.

The analysis of the motion of the electrons between cylindrical electrodes was carried out by A. Scheibe (3). The calculated wave lengths were compared with his experimental results and better agreement was obtained than using the Barkhausen and Kurz formula, the calculated wave lengths being longer in all cases. He confirmed the result of Barkhausen and Kurz that the wave length depends primarily on the potentials and the geometry of the electrodes and is practically independent of other factors. The intensities of the oscillations in both Barkhausen and Kurz's and Scheibe's experiments were small.

Gill and Morrell Oscillations. On the other hand, Gill and Morrell (4) showed that the wave length of the oscillation is determined by the resonating circuit consisting of the electrodes of the tube and the outside circuit connected to them, and that the Barkhausen and Kurz equation is satisfied only by the potential on the grid for maximum energy of oscillation. Gill and Morrell used a Lecher wire system for their outside tuning circuit. Due to its low decrement, the intensity of the oscillation was consequently larger than those of the two former cases. They assumed, though, that the period of the oscillation is equal to the time of transit when the electrons pass from the grid toward the plate and are back to the grid again. The calculated period is in good agreement with the measured results.

The maintenance of the oscillation was explained by the above authors on the ground that when the electrons pass the grid at some particular time, the work done upon the electrons by a small alternating potential on the grid and the plate can be negative. If this negative work is large enough to compensate for the resistance, dielectric and radiation losses in the oscillating circuit, undamped oscillations will be sustained.

Due to the apparent difference in nature of the oscillations produced by the Barkhausen and Kurz method and that by Gill and Morrell, they are usually distinguished from each other and named after their respective discoverers, and for brevity may be designated as BK- and GM-oscillations. There is, however, no fundamental difference between them. The distinction lies in the difference of coupling there exists between the circuit inside the tube and that used for tuning outside the tube. In the BK-experiments the oscillatory circuit was seated inside the tube, and very "loose" coupling exists between the grid and the plate. Thus any change of the circuits outside would cause only very slight change of frequency. On the other hand, in the experiments of Gill and Morrell, the oscillatory circuit consisted of a Lecher wire system connected to the grid and plate. Thus the coupling is very "tight", and the frequency is almost entirely determined by the outside circuit; the proper potentials on the electrodes only serve as a factor which enhances the intensity of the oscillations.

It is to be noticed that Scheibe calculated the period of the oscillation by taking it as the time of transit of the cycle executed by the electrons from the filament through grid to plate and back, while Gill and Morrell took it as the time of transit of the cycle from grid to plate and back to grid. They both, however, obtained results which agree very well with experimental values. Thus one of the theories must be incorrect, although both yield results which check with experiments. The discrepancy was elucidated by the works of Potapenko (5) and others (6), (7), (8), about which we shall discuss presently.

Although Gill and Morrell explained the generation of oscillations by assuming that there exists an alternating potential on the grid and plate, its magnitude was taken to be negligible. Hollman (6) first analyzed the effect of the alternating potential upon the wave length for tubes of special dimensions and showed that the wave length should be decreased by it. Kapzov (7) and Sears (8) by means of numerical and graphical integration obtained the same result. This was shown experimentally to be true by Potapenko (5). He varied the intensity of the oscillation over wide magnitudes and showed that the wave length obtained approached more closely to that calculated according to the Barkhausen and Kurz formula and still more closely to that of Scheibe, as the intensity of oscillation was decreased. The influence of this alternating potential was found to be much larger than that of all the other approximations combined including taking the cylindrical electrodes as infinite planes. In the experiments of Barkhausen and Kurz and of Scheibe the intensities of oscillation were rather low; thus little correction is needed to bring the calculated values of the wave length to agree with those found experimentally. On the other hand, the intensity was high in the case of Gill and Morrell and the wave length would be appreciably shortened by the alternating potential. So although they obtained better agreement with experimental result by assuming that the period is given by the time of transit of electrons from grid to plate and back, the real cause of the shortening of wave length is the influence of the alternating potential on the motion of the electrons. Thus the success of a theory to account for the oscillation depends on an analysis which takes into consideration all the factors, especially that of the alternating potential.

Higher Order Oscillations. On account of the limitation in the size of the electrodes of a tube that can be made and the amount of heat the grid of the tube can safely dissipate, the shortest wave length that can be obtained using the BK- or GM- scheme is of the order of 30 cm. To push the wave length to still shorter values one has to find recourse in the method of generating waves of higher orders. Potapenko (9),(10),(5) made a systematic study of such waves and showed that waves of wave lengths scores of times shorter than that calculated from the Barkhausen and Kurz formula can be produced. These are different from harmonics or overtones due to the complete absence of the fundamental. He showed that the wave lengths of these higher order oscillations and the grid potentials satisfy the following equation:

$$n^2 \lambda^2 E_g = C,$$

where C is a constant; and n, an integer, 2,3,4, etc. When n is equal to 1, it reduces to the familiar Barkhausen and Kurz equation. When n is equal to 2, 3, etc., they may be called the second, third, etc., order oscillations respectively. The constant C depends upon the intensity of oscillation, and when the latter approaches zero, the constant becomes nearly equal to Scheibe's value. The above equation shall be called the Potapenko equation. As the time of transit of the electron cycle is fixed by the geometry of the electrodes of the tube and their potentials, the period of the higher order oscillations are integral fractions of the transit time. Graphical integration of the electron paths showed that oscillation under such circumstances is possible.

The importance of the higher order oscillations to the generation of very short waves is apparent. It affords a means of reducing the period of the oscillation beyond the time of transit of the electrons. To decrease the wave length by a ratio of 4:1, for instance, an increase of grid potential by the ratio 16: 1 is required using the BK- or GM- oscillations. But when the tube is made to oscillate at the fourth order, the same reduction in wave length can be accomplished at the same grid potential. These higher order oscillations take place readily whenever there are sharply tuned circuits inside the tube, such as the grid helix, the plate helix, etc. Thus with proper design it is possible to accentuate certain wave lengths. It is the object of part of the present work to investigate the limit of wave length that can be obtained with this scheme.

ON THE MOTION OF THE ELECTRONS BETWEEN THE ELECTRODES

Tubes with concentric cylindrical electrodes are used more frequently than those with other types of electrodes in generating oscillations with the retarding field method. In the first place they are simpler to make, and secondly strong oscillations can be generated easily. Tubes with plane electrodes were used only in those investigations, the object of which was to study the effect of the shape of the electrodes upon the oscillations. Unfortunately the equation of motion of the electrons between cylindrical electrodes can not be solved in the general case, as we shall see later. The simple analysis for plane electrodes, however, gives results in fairly good agreement with experimental results, and the equation it leads to is useful as a guide in designing tubes. We shall now consider this case:

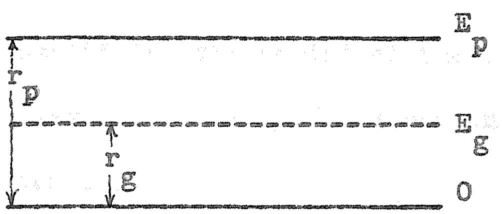

Figure 1.

Let E_g and E_p be the voltages on the grid and plate respectively; and r_g and r_p their respective distances from the filament. The potential of the filament is taken as zero. e, m, v, are the charge, mass and velocity of the electron respectively. Let us assume that:

1. The electrodes are equi-potential surfaces;
2. The field between them is uniform;
3. There exists no space charge effect;
4. The alternating potentials on them are negligibly small; and
5. The electrons are emitted from the filament with negligible initial velocities.

In the grid-filament space:

The average velocity of an electron $\bar{v}$ is:

$$\bar{V} = \frac{1}{2}\sqrt{\frac{2eE_g}{m}} = \sqrt{\frac{eE_g}{2m}}$$

Time required to travel from the filament to the grid is:

$$t_1 = \frac{r_g}{\bar{v}} = \sqrt{\frac{2m}{eE_g}}\, r_g$$

After passing the grid the electrons face a retarding field and will be brought to a stop at a distance r_u from the filament where the potential is zero.

$$r_u = \frac{E_g(r_p - r_g)}{E_g - E_p}$$

Since the mean velocity is the same as in the former case, the time from grid to the return point is

$$t_2 = \sqrt{\frac{2m}{eE_g}}\,\frac{r_p - r_g}{E_g - E_p}\,E_g$$

Identifying the period of the oscillation as the time for the cycle from filament to grid-plate space and back to filament, the period of oscillation is:

$$\tau = 2(t_1 + t_2) = 2\sqrt{\frac{2m}{eE_g}}\,\frac{E_g r_p - E_p r_g}{E_g - E_p}$$

The wave length λ is:

$$\lambda = c\tau \cong 2000\,\frac{1}{\sqrt{E_g}}\,\frac{E_g r_p - E_p r_g}{E_g - E_p},$$

the potentials being in volts and the diameters in cm. In the special case when the plate is connected to the filament, the equation reduces to the familiar form:

$$\lambda^2 E_g = d_p^2 10^6,$$

where d_p is the diameter of the plate.

Analysis of the Motion of Electrons between Cylindrical Electrodes.

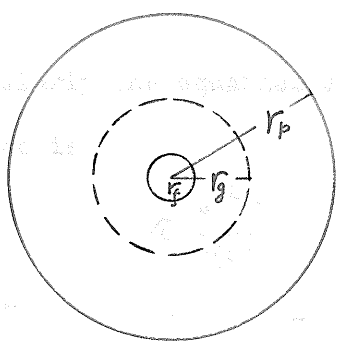

Figure 2.

Similar to the preceding analysis we shall assume that:

1. The electrodes are equi-potential surfaces along their lengths;
2. The field is not distorted by the finite lengths of the electrodes;
3. There is no space charge effect.

Let the constant potentials on the grid and the plate be V_{cg} and V_{cp} respectively. Let V_{og} and V_{op} be the amplitudes of the alternating potentials on them. The potential on the grid at any time is

$$V_g = V_{cg} + V_{og} \sin(\omega t + \alpha)$$

where α is a phase constant which takes care of the fact that the alternating potential may be at any phase when the electrons start their trips. The potential at any distance r from the axis is

$$V_r = \frac{V_g}{\log_e \frac{r_g}{r_f}} \log_e \frac{r}{r_f}$$

The field at point r is

$$E_r = -\frac{V_g}{\log_e \frac{r_g}{r_f}} \frac{1}{r}$$

The equation of motion of the electrons is then,

$$m\frac{d^2r}{dt^2} = E_r e = -\frac{V_{cg} + V_{og}\sin(\omega t+\alpha)}{\log_e \frac{r_g}{r_f}}\,\frac{e}{r}$$

or

$$r\frac{d^2r}{dt^2} = A\left\{1 + B\sin(\omega t+\alpha)\right\}$$

where

$$A = -\frac{e}{m}\,\frac{V_{cg}}{\log_e\frac{r_g}{r_f}},$$

and

$$B = \frac{V_{og}}{V_{cg}}$$

Similarly the equation of motion of the electrons in the grid-plate space is

$$r\frac{d^2r}{dt^2} = A'\left\{1 + B'\sin(\omega t + t_1 + \alpha) - B''\sin(\omega t + t_1 + \delta)\right\};$$

where

$$A' = \frac{e}{m}\,\frac{V_{cg} - V_{cp}}{\log_e\frac{r_p}{r_g}}$$

$$B' = \frac{V_{og}}{V_{cg}-V_{cp}}, \quad B'' = \frac{V_{op}}{V_{cg}-V_{cp}}$$

Unfortunately equations of the above type do not admit integration in quadrature or in terms of known functions. By assuming special values for the magnitudes concerned, the paths of electrons can be found by the step-by-step method of integration or by using graphical means.

Kapzov (7) investigated the special case when the constant plate potential is zero and the alternating potentials on the plate and grid are equal in magnitude and opposite in phase. Sears (8) repeated it with a continuous integraph. Their results have already been mentioned on page 6.

In the special case when the alternating potentials on the electrodes are negligible the above equations are reduced to forms which can be integrated in terms of known functions. In this case, we have the equation of motion in the grid-filament space

$$r\frac{d^2 r}{dt^2} = A$$

Integrating and assuming that the initial velocity of an electron is zero,

$$\frac{dr}{dt} = v = \sqrt{2A\log_e\frac{r}{r_f}}$$

The time from filament to grid is

$$t_1 = \frac{2r_f}{\sqrt{2A}}\int_0^{\sqrt{\log_e\frac{r_g}{r_f}}} e^{x^2}\,dx$$

where

$$x^2 = \log_e\frac{r}{r_f}$$

Similarly for the grid-plate space

$$t_2 = \frac{2r_g\left(\frac{r_p}{r_g}\right)^{\frac{V_{cg}}{V_{cg}-V_{cp}}}}{\sqrt{2A'}}\int_0^{\sqrt{\frac{V_{cg}}{V_{cg}-V_{cp}}\log_e\frac{r_p}{r_g}}} e^{-y^2}\,dy$$

where

$$y^2 = \frac{V_{cg}}{V_{cg}-V_{cp}}\log_e\frac{r}{r_g}$$

The wave length is

$$\lambda = c\tau = 2c(t_1+t_2) = \frac{4cr_f}{\sqrt{2A}}\int_0^{\sqrt{\log_e\frac{r_g}{r_f}}} e^{x^2}\,dx + \frac{4cr_g}{\sqrt{2A'}}\left(\frac{r_p}{r_g}\right)^{\frac{V_{cg}}{V_{cg}-V_{cp}}}\int_0^{\sqrt{\frac{V_{cg}}{V_{cg}-V_{cp}}\log_e\frac{r_p}{r_g}}} e^{-y^2}\,dy$$

The second expression is the Gaussian error integral and the first one can be found in tables, (for instance Proc.London Math. Soc. Vol.29, pp 519-522, 1898). This last equation corresponds to Scheibe's equation. The constants of the tubes investigated in the present work were calculated from both the Barkhausen and the Scheibe equations.

EXPERIMENTAL

The Pliotron FP-126 as a Retarding Field Oscillator. The Pliotron FP-126 is a thermionic tube designed for use as an oscillator by means of the retarding field method. There are three electrodes of the concentric cylinder type. The filament is a straight wire of pure tungsten with a diameter of 0.025 cm. It is supported at each end by a stout tungsten wire which is sealed through the glass envelope of the tube. The length of the filament is about three centimeters long. The grid is a helix of 14 turns of wire. A U-shaped wire joins to-gether the two ends of the helix, thus forming a closed circuit inside the tube. The diameter of the helix is 0.65 cm. The physical length of the grid wire to-gether with the U-shaped support is about 35 cm., the length of the latter being 4.9 cm. The plate is a cylinder made of wire gauze of close mesh. Its inside diameter is 1.65 cm. The lead wires of the electrodes are not sealed in the conventional press, but are sealed individually so that they are as widely separated as practicable. No conventional tube base is attached to the tube.

The amount of power that can be dissipated in the tube is limited by the safe operating temperature of the grid. Nearly all the heat is transfered from the grid by means of radiation. By making the plate out of wire gauze the heat from the grid can be radiated freely through its open spaces. If the plate were made of sheet metal, the heat from the grid would be reflected back and forth until it is absorbed and re-radiated by the plate. Thus to make the plate out of wire gauze allows the grid to be operated at a lower temperature for the same input.

A very constant thermionic emission from the filament is very essential for maintaining a stable oscillation by the retarding field method. This necessitates the use of pure tungsten filament instead of the thoriated tungsten or oxide-coated ones. The latter two are more efficient in their emission, but it is impossible to keep the emission constant, though the filament current is maintained constant.

From the construction of the tube, we see that the grid helix forms a tuned circuit by itself. The inductance and capacity of the circuit are "lumped", and the coupling to the outside circuit is very "loose"; therefore there exists very little radiation loss. Both ends of the helix are welded to the U-shaped wire; so its resistance loss is also low. Its remoteness from the glass envelope and seal reduces the dielectric loss. Therefore we expect the grid circuit to be one of low decrement. Whenever the potentials of the electrodes are such that the corresponding frequency is near the natural frequency of the grid circuit, these oscillations will be very much enhanced. From the dimensions of the tube elements a rough calculation shows that it requires a grid potential of the order of 2000 volts to generate the normal oscillations of this wave length. Therefore at lower grid potentials, we can only expect oscillations of higher orders.

The constant $\lambda^2 E_g$ is calculated from both the Barkhausen-Kurz and the Scheibe formulas. Their values are as follows.

$$(\lambda^2 E_g)_B = 2.72 \cdot 10^6$$
$$(\lambda^2 E_g)_S = 2.52 \cdot 10^6$$

<u>Arrangment of Apparatus</u>. The arrangement of our apparatus was essentially the same as that developed and used by Potapenko (11). A schematic diagram of the apparatus is shown in figure 3. The two grids

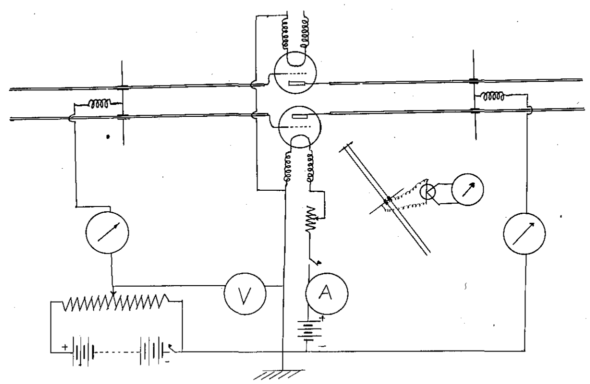

Figure 3
Schematic Diagram of Apparatus

of two similar FP-126 tubes form the terminals of two Lecher wires on one side and the plates form the terminals of the Lecher wires on the other side of the tubes. The negative terminal of the filament serves as the zero potential from which the grid potential is measured. The plate was connected to the negative end of the filament in all the measurements. Filament current was supplied by two six-volt storage batteries connected in parallel. A rheostat with a vernier adjustment regulated the filament current very smoothly. When a complete set of measurement was taken in the course of several weeks, extreme care was taken each time in adjusting the filament current to a constant value. Since the emission current varies very rapidly with the filament temperature, ordinary ammeters are not sensitive enough to set the filament current to make the results reproducible. Therefore accurate regulation of filament current was accomplished by adjusting the emission current to a constant value at a definite grid potential, which was supplied by a bank of storage batteries of large capacity when the voltage used was less than 250 volts, and by a d.c. motor generator or a well filtered power pack when the voltage was above that value. The voltage was regulated with a potentiometer with a vernier adjustment.

Wave length measurements were made with a Lecher wire system loosely coupled to the grid or plate tuning systems or to the tube, depending on where the oscillations were stronger. Wave lengths longer than 60 cm. were measured with a Dr. L. Rohdes wave meter.

To investigate the behavior of the tube and the mechanism of the oscillations, much higher grid potentials than the rated were used in the following experiments. In order not to exceed the safe dissipating power of the grid, the emission current was reduced below rated values by regulating the filament heating current. Under the heaviest loading conditions, the grid was heated to only a cherry red.

<u>The Working Diagram</u>. The investigation of the working mechanism of a tube and a complete picture of its behavior can best be made by means of the so-called "working diagram", which was developed by Potapenko (9). In this scheme, the relation between the intensity of oscillation, the grid potential and the tuning system connected to the elements of the tube is indicated in the same diagram. The tuning systems of the plate and the grid which consisted of two Lecher wire systems were first fixed by setting the movable bridges at certain positions. The grid potential was gradually varied from zero to about 1000 volts. A current

in the plate circuit is an indication of the existence of oscillations; for otherwise the electrons could not reach the plate, which is at a lower potential than the average potential of the filament. For a certain tuning condition there are generally several grid potentials at which oscillations occur. The plate current passes through a maximum value at the point of maximum energy of oscillations, when the grid potential is varied. The plate current, the grid potential and the positions of the movable bridges of the Lecher wires were noted and the wave lengths measured at these points of maximum plate current. The positions of the bridges were then changed by small distances and the process repeated. In this manner, the intensity and wave length of oscillations and the grid potential at which the oscillations occur for all adjustment of grid and plate tuning were found. The grid potentials were plotted against the readings on the tuning Lecher wires as abscissa. The points fall into separate curves. The plate current and the wave length should vary continuously along these curves; so they serve as a guide in joining the points into the separate curves. The working diagram of FP-126 No. 201 is shown in figure 4.

<u>The Normal Oscillations</u>. The most predominating mode of oscillations is the generation of normal waves, i.e. those whose wave length is given approximately by the formula of Barkhausen and Kurz. There are four branches of the curve due to normal oscillations in the working diagram. These are generated in the circuit which consists of the elements of the tube, their leads and the Lecher wires attached to them. Since the latter constitutes a large fraction of the total circuit and the coupling is very tight, the dependence of oscillation upon tuning is very large. The decrement of the circuit is rather small; consequently the normal oscil-

lations are intense and take place with a wide range of grid potential at approximately the same frequency. For example, at $L = 45$ cm., the normal oscillations start at 168 volts and stop at 250 volts. The wave lengths are as follows:

$E_g =$ 168 volts; Average wave length = 95.4 cm.,

$E_g =$ 250 volts; Average wave length = 95.0 cm.

The points plotted are those where the intensities are maxima. Let the elements of the tube and their leads be equivalent to a constant length of Lecher wires, then by moving the bridges on the Lecher wires through a distance δL, the natural wave length of the system is changed by $4\delta L$, when the Lecher wire is one quarter wave length long; by $2\delta L$ when it is two quarter waves; by $\frac{4}{3}\delta L$ when it three quarter waves; etc. For the same grid potential, the Lecher wires have to be changed by $1/4\delta\lambda$, $1/2\,\delta\lambda$ $3/4\delta\lambda$, etc., when it is $1/4\lambda$, $2/4\lambda$, $3/4\lambda$, etc. long respectively. Or in other words the slopes of the different branches of the curve at the same grid potential must be different - the branch corresponding to the condition that the tuning Lecher wire is comprised of more quarter wave lengths has the smaller slope. This is seen clearly to be the case from the diagram.

Oscillations of Higher Orders. All the other curves correspond to oscillations of higher orders. They fall distinctly into two classes. There are three curves which follow a similar course to that of the normal oscillations; so they are generated in the same tuning system. Their wave lengths are, however, only approximately one half or one third of that calculated from the Barkhausen formula, depending on the order. These will be useful as a source of continuously varying short wave length not obtainable in the form of normal waves due to the high grid potential

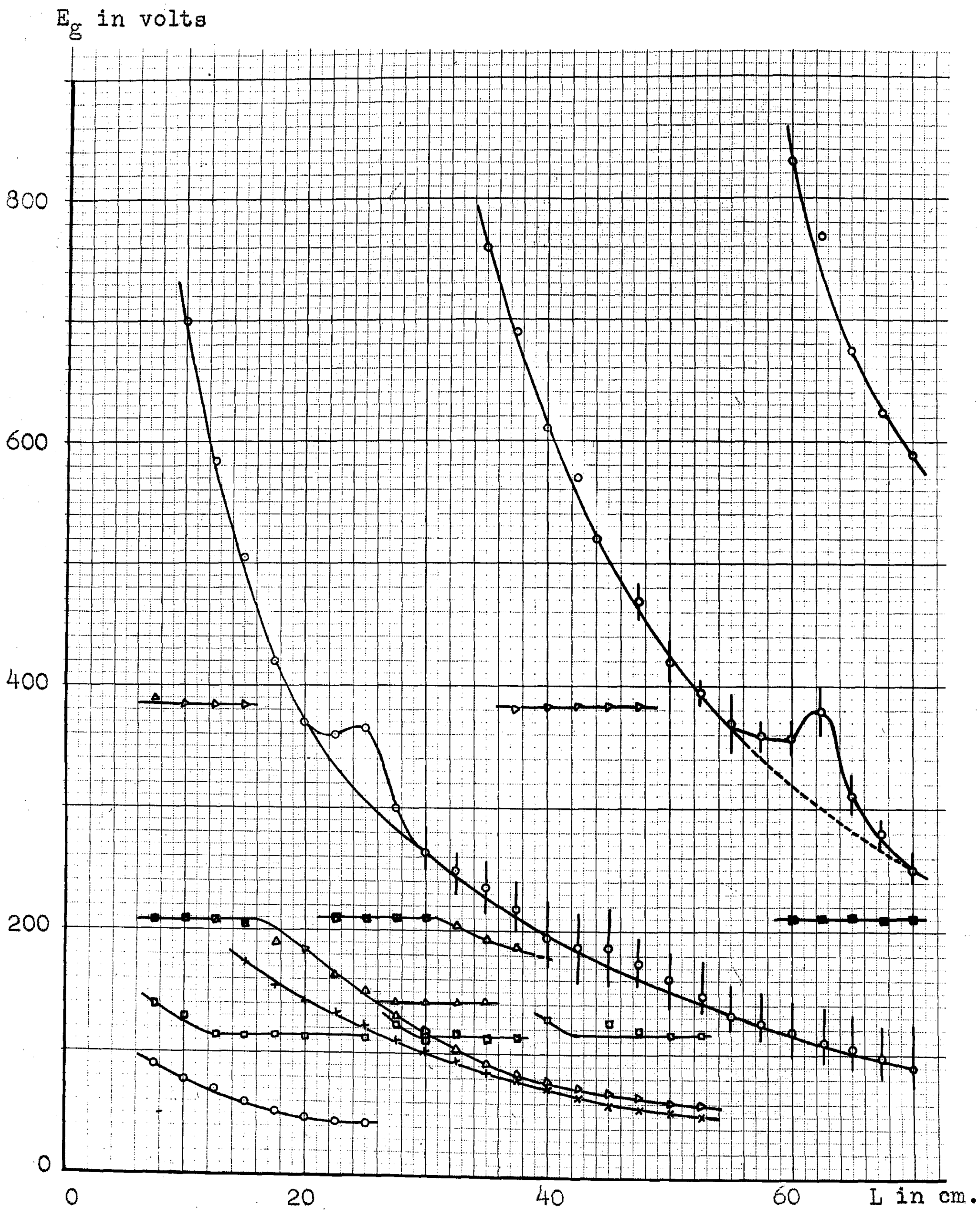

Figure 4

The Working Diagram of FP-126, No. 201

o Normal Oscillations
× 2nd Order Oscillations
△ 3rd Order Oscillations
□ 4th Order Oscillations

necessary. Unfortunately they cease to oscillate at grid potentials higher than 200 volts and the intensity is much lower than that of the normal waves.

The rest of the curves run nearly parallel to the abscissa. This shows that they are independent of tuning, and must have their seats of oscillations inside the tube with the tuning system very loosely coupled. They occur at three grid potentials, viz. 385, 210 and 114 volts. The wave length at 385 volts is 25.4 cm., and calculation shows that the oscillations are of the second order. The oscillations at 114 volts have a wave length of approximately 35 cm. and they are of the third order. Both of these oscillations occur simultaneously at 210 volts, the 25.4 cm. wave being much more intense than the other. In order to reveal the origin of these oscillations, a search coil of small dimensions was connected to the heater of a thermocouple and the current generated when the search coil was placed near different parts of the tube was noticed. It was thus found that the 25.4 cm. oscillations are produced in the grid coil and the 35 cm. oscillations in the leads of the tube. It happens incidentally in this particular tube that the grid potentials required to excite the 25.4 cm.waves as the third order and the 35 cm. waves as the second order coincide, having the value 210 volts. From the construction of the tube we expect strong characteristic oscillations with a frequency equal to that of the natural frequency of the grid coil. The latter was calculated from the dimensions of the grid coil using Drude's results (12) and was found to be 25.2 cm.

The separation of the waves into normal oscillations and those of higher orders can be seen more clearly when the wave lengths are plotted against the grid potentials. This is shown in figure 5. For any grid potential there are in general more than one wave length. However, they all follow the curve $\lambda^2 E_g = $ Constant, the constant being different for the different curves. The average values of these constants are tabulated in the following table to-gether with those calculated from the Barkhausen and Scheibe equations.

		$\lambda^2 E_g \times 10^6$	n	$n^2 \lambda^2 E_g \times 10^6$
Calculated	Barkhausen	2.72		2.72
	Scheibe	2.52		2.52
Observed (average)	Normal Osc.	1.52	1	1.52
	2nd order Osc.	0.635	2	2.54
	3rd order Osc.	0.256	3	2.30
	4th order Osc.	0.143	4	2.28

It is seen that the values of the constants of the higher order oscillations multiplied by the squares of the order numbers are very nearly equal to that calculated from the Scheibe equation. The value of the constant of the normal oscillations deviates considerably from the calculated values. This deviation can be accounted for by the effect of the alternating potential of the electrodes upon the frequency. The results indicate that the wave length of the normal oscillations is decreased by the alternating potential, confirming the predictions of Epstein's theory and Potapenko's results (5).

The foregoing shows that the tube FP-126 gives strong normal and higher order oscillations. The former can be generated by coupling a tuning system of low decrement to the electrodes of the tube and the latter arises

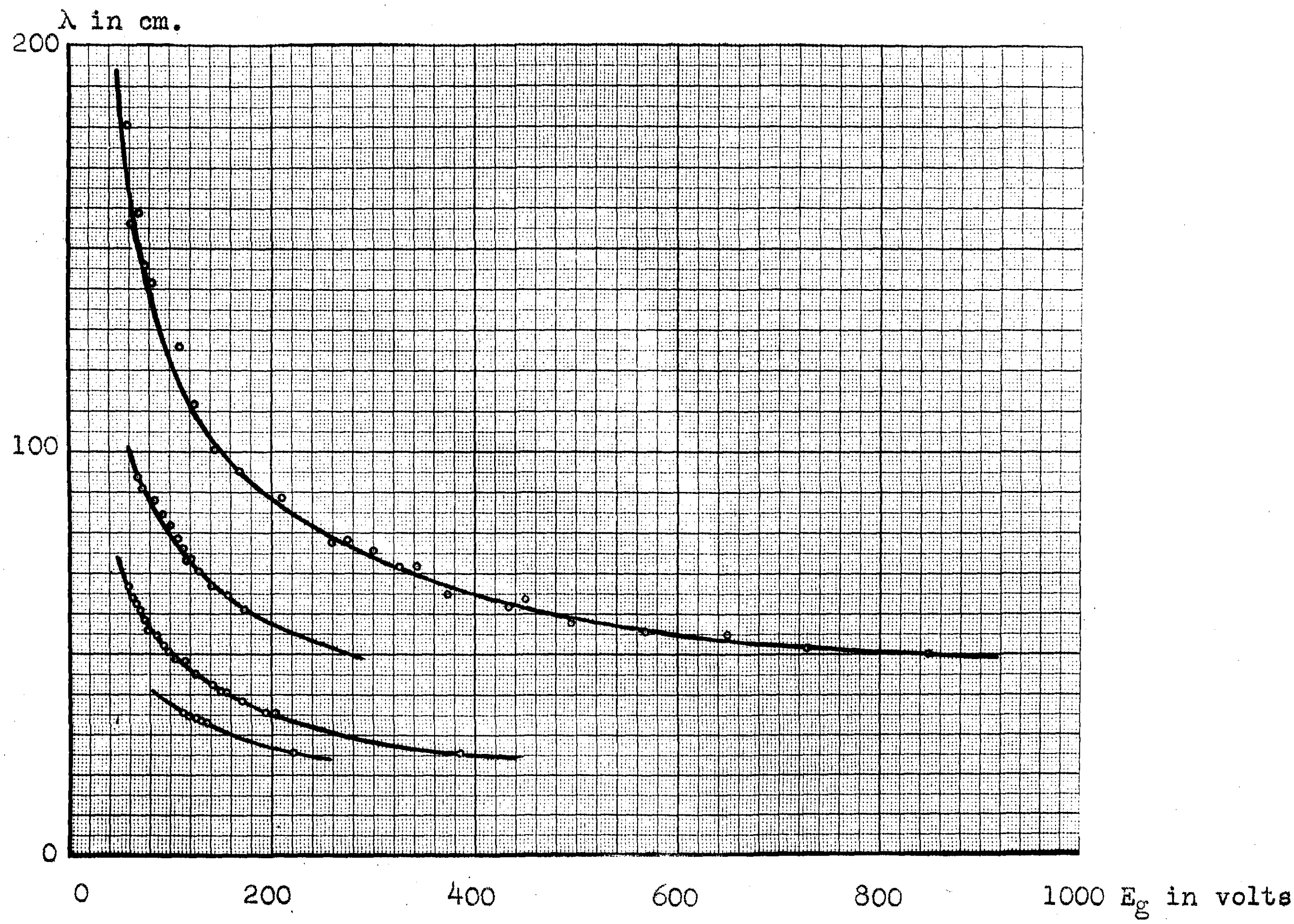

Figure 5

Curves Showing the Relation between the Wave Length and

Grid Potential at Maximum Intensity

of Oscillation

from the natural frequency of the grid coil and is practically independent of tuning. The wave lengths are given approximately by the Potapenko equation.

Tubes for Centimeter Waves.

Principle of the Design. It is seen from the above experiment that the operation of a tube follows the Potapenko equation closely. In this equation we see that there are three factors we can control in the design of a tube for very short wave lengths. These are the grid potential, the plate diameter and the order of oscillation. By raising the grid potential, the wave length becomes shorter and shorter. Since the wave length is inversely proportional to the square root of the grid potential, the rate of shortening of wave length with respect to the grid potential is inversely proportional to $(E_g)^{\frac{3}{2}}$. This can also be seen from the $\lambda - E_g$ curves (fig. 5). The slope of the curves becomes almost tangent to the E_g - axis at the higher grid potentials. The rate of heat dissipated on the grid varies as the first power of the grid potential, so that very soon a limit is reached beyond which the grid will be overheated. Actually the limit is reached much sooner, for the tube ceases to oscillate at the higher grid potentials unless the emission current is increased.

The wave length is proportional to the diameter of the plate. Thus by decreasing its magnitude the wave length can be shortened much more efficiently than by raising the grid potential. Evidently there is a limit to the smallest physical size of the plate that can be manipulated. Further, as the plate diameter is reduced, the grid must be reduced accordingly. This imposes a serious limitation upon the heat dissipating capacity of the grid. Let us take the example of a linear reduction of ratio

2:1 of the elements. The wave length will be decreased by a ratio of 2:1 also, while the area of the grid will be decreased by a ratio of 4:1. Nearly all the heat which the grid must dissipate has to be radiated. The radiating power of the grid is proportional to its area. Thus the safe grid dissipation is decreased rapidly with the reduction in size.

Further reduction in wave length can only be accomplished by utilizing the higher order oscillations. The foregoing experiment with Tube FP-126 shows that very strong oscillations of the same wave length take place whenever the grid potential is favorable for its generation. These oscillations were shown to be those of the grid at its natural frequency. This fact can be utilized in the design of tubes. It is important that this circuit be made with as small a loss as possible. Oscillations can occur only when the energy supplied by the electron stream compensates the losses in the circuit. If we assume that the grid coil radiates like a Hertzian dipole, the radiation loss will increase sixteen fold whenever the wave length is decreased by a factor of two. The resistance of the circuit will also be increased due to the decrease in the depth of the conducting layer or the so-called "skin effect" at high frequencies. Due to all of these unfavorable factors towards the generation of very short waves, we may expect its intensity to be low.

The procedure in designing a tube can be exemplified by the following. The smallest diameter of the plate that can be easily manipulated may be taken as 0.05 cm. The constant of the Potapenko equation is $N^2\lambda^2E_g = d_p^2 10^6 = 2500$. Simple calculation shows that a wave of one cm. should be obtainable at grid potentials equal to 100 and 70 volts when n is equal to 5 and 6 respectively. These are reasonable values for the grid potential and n . It was shown by Gossel (13) that the best ratio of the diameter of the plate to that of the grid is about 3. This condition determines the grid diameter at about 0.02 cm. The total length of the grid wire should be about equal to the wave length. This fixes its number of turns. The length of the grid coil depends on the distance between the successive turns. Now the clearance between the grid wires should not be too small, for otherwise, a majority of the elctrons will be caught by the grid on their flight from the filament to the plate, thus becoming useless for oscillation. On the other hand, it can neither be too large, for the field due to the grid will be very much distorted and the electrons from the filament will pass the grid with widely different velocities and the oscillation energy will be decreased due to the incoherency of the electrons. Tubes which yield strong oscillations like the FP-126 and others have a clearance to grid wire diameter ratio of 5 to 6. Taking the same ratio for this tube, the length of the grid helix and consequently the plate length are fixed. The filament wire may have any convenient diameter for even the thinnest filament obtainable will be able to furnish more emission current than can be stood by the grid. The actual dimensions of the elements of the tubes made differ from one another.

Construction of the Tubes.

The Plate. The plate is made of pure nickel tubing. Nickel was used for it is available in tube form and on account of its ductility it can be drawn to the desired inside diameter. A steel wire having a diameter equal to that of the desired inside diameter of the plate was put inside the nickel tubing and they are drawn through a wire drawing die. They were drawn through a series of holes of gradually diminishing diameter until the nickel tubing surrounded the steel wire very snugly. A segment of the tubing of the required length was cut off from the rest with a razor blade. This was used as the plate in the assembly of the tube.

The Grid. The grid material must have the following properties. It must have a small electrical resistivity so as to make the loss of the grid circuit as small as possible. Its melting point must be high, for under the bombardment of the electrons at high grid potentials a large amount of heat is generated. It has to keep its shape at high temperature. There are four materials which answer these requirements with varying degrees of satisfaction. These are tungsten, platinum, tantalum and molybdenum. An examination of the properties of these four reveals that tungsten is the best one for this purpose. Molybdenum has a resistivity about ten percent smaller than that of tungsten, but its melting point is about 30 per cent lower. Tantalum has the superiority over tungsten in that it absorbs a large amount of gas at high temperatures, but the tubes will be under constant pumping during operation and this advantage is not important compared to its inferiority of having a resistivity three times larger. Furthermore, tungsten is available in wires of different diameters, so this is used in all the tubes. Its stiffness makes it very desirable for keeping its shape even at high temperatures, but at the same time it presents a difficulty in making a grid helix having a uniform diameter and constant pitch.

Different methods were tried in making the grid, and after some experimenting the following method was devised and found to be very satisfactory. The grid winding instrument is very simple and is shown in figure 6. It consists of a rectangular framework the two long sides of which were made of aluminum and the two end pieces, of ebonite. Through the middle of each of the long pieces was attached a brass rod a upon which the whole frame work can be rotated on supports b. A hole was drilled through each brass rod so that a steel wire can be passed through and fastened by the setting screws c. To wind the helix, a steel wire of the appropriate diameter was passed through the holes of the brass rods and fastened by the screws after being stretched taut. A piece of very straight tungsten wire was then fastened to d, and a weight was attached to the other end. By rotating the frame work on its supports the tungsten wire winds itself very uniformly around the steel wire. The pitch of the grid helix was controlled by tilting the axis of the frame work relative to the plumb line. The tungsten wire would unwind itself if the grid is taken off at this stage. To keep it in the desired diameter a current was passed through the steel wire till the latter was heated to about 400° C. The the tungsten wire was cut off from the weight and its support and the steel wire removed from the frame work. At first acid was used to etch away the steel wire, but after one has learned the technique, one can cut the steel wire at the end and slide the grid off with-

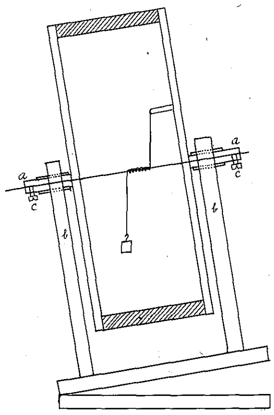

Figure 6
The Grid Winder

out difficulty. In this way grid helices of any diameter and pitch can be made rather quickly.

<u>The Filament</u>. Pure tungsten wire is used for the filament. Its emission efficiency is much lower than that of thoriated tungsten, but has the advantage of giving a constant emission current. Thoriated tungsten filament can only be operated at the temperature where the rate of evaporation of the thorium from the surface of the filament is equal to the rate of supply of the same. As the emission has to be varied over wide limits when the tube is used as a retarding field oscillator, the use of thoriated tungsten is out of question. To secure a piece of tungsten wire straight enough for the filament presented much more trouble than one would expect. There are usually sharp bends and curvatures in these wires that are impossible to be straightened out mechanically without heating. Heating the thin wire in air resulted in oxidizing it so badly that it broke easily when manipulated. Heating electrically in carbon dioxide under tension from an attached weight was next tried. The up-rising current of heated carbon dioxide gas cooled the upper part of the wire so much that the kinks and curvatures were not straightened out, while its lower part was broken on account of the high temperature. Tungsten wires straight enough to be used as filaments for these tubes were finally successfully secured by heating them electrically in vacuum under tension.

<u>The Assembly of the Tubes</u>. At very high frequencies, nothing can be trusted as good insulators. Ordinary vacuum tubes have their elements supported, by wires sealed through a "press". The proximity of the leads and the long seal of glass in these presses can result in excessive losses.

As far as it is necessary to have the leads, they should be separated as far as practicable and very short glass seals should be used. More important than the above two factors is the place where the seals are made. Standing waves are formed along the leads, so that by placing the seals at the voltage nodes, the dielectric loss can be greatly reduced. The elements were attached to the ends of their respective supports by spot welding. This completes the assembly. After the electrodes were centered under magnifying glasses, the tube is sealed to a glass envelope and ready for evacuation.

Experimental Difficulties and How They Were Overcome. After the problem of making the plate and grid and securing the wire for the filament was solved, the actual assembly of the tube presented no less difficulty. The plate had to be mounted without being deformed. At first it was attached to the support with a paste of colloidal carbon. This held the plate, furnished electrical conductivity, and was able to stand a high temperature. Later it was found possible to weld the plate electrically to the support without any visible deformation. It was done in the following manner. The plate after it was cut to the desired length was slid on a copper wire whose diameter is slightly smaller than that of the plate. The copper wire was used as one electrode of the welder. A copper"pencil" with a small round nose formed the other. The support wire for the plate was held on the nickel tubing so that they touched each other only at the point where the nickel tubing was tangent to the copper wire inside. They were then welded with the copper pencil. After one has acquired the feeling of handling and welding small objects, it is not difficult to weld the grid and filament to their supports.

The elements were welded as nearly concentric as possible so that only very small adjustments were needed. The actual concentric alignment of the elements can be done rather easily.

A serious difficulty was encountered in keeping the filament concentric when it is heated. There are two factors which tend to throw it out of the center. The first one is due to thermal expansion. Being made of pure tungsten, the filament has to be heated to a rather high temperature before it emits copiously. Let its temperature be 2500° C. A filament 5 mm. long will be expanded by approximately 0.06 mm. If the supports remain the same distance apart, the center of the filament can be deviated from the original position by about 0.3 mm., assuming that the filament sags into an arc. Since the clearance between the filament and the grid of tube P-1 was only 0.1 mm., this sagging would result in a short circuit of the two. Now if a tension along the filament is applied, it is very apt to result in a breakage. There are hot spots at certain parts of the filament where it is thinner than elsewhere. Such a spot will yield to the tension more readily than its neighboring spots and will lengthen itself and get still hotter. Thus it works in a circle and will eventually result in a rupture. Measures were taken during the adjustment of the electrodes so that the supports would move by the calculated amount of expansion of the filament and no more. But still this does not prevent the filament from getting out of alignment when it is cooled and reheated. After the filament is heated to a temperature where it becomes plastic, it is unable to pull the supports back to their original positions and resume its original length, when it is cooled. Thus on a second heating there is no tension on the supports to keep them from sagging, and we face the same difficulty as when we started. This perhaps explains why some tubes oscillated on first trial but refused to do so when they were tried again. A spring with a very small force constant will be helpful, but one has to pay the price with a decrease in rigidity.

The second factor which tends to change the position of the filament when it is heated may be explained with the help of figure 7a and 7b. Figure 7a shows the filament in the well centered position with respect to the grid when it is cold, with a slight bend at a, exaggerated for the purpose of explanation. When the filament is heated, the bend yields to the tension of the supports, and straightens itself out. As the total diameter is only two tenths of a mm., any slight dislocation of the filament will result in serious eccentricity of the filament and make it in-operative. As a matter of fact, this was the reason why the filament wire was straightened in vacuum as mentioned above. For further prevention of this effect, the part of the filament outside of the useful portion was covered with the paste of colloidal carbon. This furnished a larger and more efficient radiating surface to keep the temperature of the non-operative portion below the yielding temperature. It also decreased greatly the emission from the same portion, thus eliminating the unnecessary heating of the grid. Thermal expansion of the filament was also greatly reduced which lessened the amount of sagging.

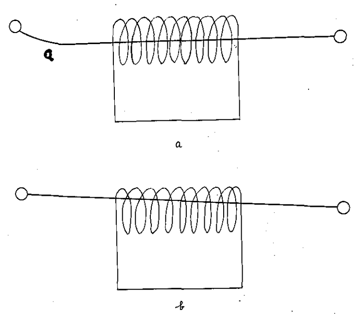

Figure 7

After a tube was assembled and aligned to symmetry, it was sealed to the vacuum and evacuated. The vacuum system consisted of two stages of mercury diffusion pumps. Since the tubes were not intended to be sealed off, glass tubes of large bores were used for connections. The vacuum path of low impedance and a system of small volume were used to insure great pumping speed. The tube was "baked" at about 400° C. for several hours or more to make the glass surfaces of the tubes free of adsorbed water vapor and gases. The electrodes were freed from occluded gases by heating them to redness with electron bombardment. Such bombardment evaporates the layer of oxide from the tungsten wire of the grid, leaving a clean bright surface. It was found during the preliminary experiments that the vacuum must be very high for the generation of oscillations, especially the higher orders. Tubes which showed no oscillations when they were first tried worked well after being baked thoroughly. The vacuum was measured with a Mcleod and an ionization gauge. The vacuum was always better than 10^{-6} mm. of mercury.

From the dimensions of the tube and the potential the grid can stand, we could expect to generate waves of about 1 cm. in length in the form of of higher order oscillations only. To supress the normal oscillations, the electrodes were connected to the proper sources of potential through current meters without any tuning system which was used in the study of the tube FP-126. The plate was connected to the negative terminal of the filament. The grid potential was then varied. A plate current in the right direction indicated the presence of oscillations.

More than twenty small tubes were made. In studying them, both normal and higher order oscillations were observed. The normal oscillations, being suppressed as mentioned above, were low in intensity. They took place in most tubes when the concentricity of the elements remained good after the electron bombardment and pre-heating. These nornal oscillations were originated in the leads as their prime resonating circuits. Their wave lengths were measured by sliding a movable bridge along the lead wires and noticing the positions of the voltage nodes. They were found to be very nearly equal to the values calculated from the dimensions of the tube from the Barkhausen equation, as it should be the case, when the intensities were low. As we were primarily interested in the oscillations of higher orders, the normal oscillations were examined only to distinguish them from the former. From our study of the tube FP-126 we have seen that the normal oscillations can be easily told apart from the oscillations of higher orders by their characteristics. In the first place the higher order oscillations have a sharp peak when the grid potential is varied. Secondly, the normal oscillations are affected greatly by the tuning system connected, but the higher order oscillations are practically independent of it. Thirdly, the intensity of the normal oscillations is usually higher than that of the higher order oscillations. These three properties distinguish one kind of oscillations from the other with certainty.

As we have seen before, the wave length of the most predominating waves can be calculated approximately from the dimensions of the grid. In the case of FP-126 the calculated value agrees with the observed wave length to less than 1 per cent. The grid potential required to produce the predicted wave lengths for the different orders of oscillations can be calculated from the constant of the tube and the order number. This constant was computed from both the Barkhausen and the Scheibe equations. The grid potentials calculated in this way were compared with the observed values where oscillations of higher orders occured, Their being oscillations of higher orders and not the normal waves was determined by their distinct properties as mentioned above. This comparison is given in the following table for two tubes which generated oscillations of higher orders more readily than the other tubes.

DIMENSIONS OF THE TUBES

Type and No. of Tube	P-1, No. 6	P-1, No. 10
Plate diameter	0.0539 cm.	0.0539 cm.
Grid diameter	0.020 cm.	0.020 cm.
Length of grid coil	0.1 cm.	0.08 cm.
Drude's factor for grid coil (l λ)	0.70	0.74
Length of grid wire from one welding point to the other	1.22 cm.	1.21 cm.
Natural wave length of grid	0.97 cm.	1.00 cm.
Diameter of filament	0.0025 cm.	0.0025 cm.

The Calculated Grid Potentials and Observed Values of P-1, No.6 and P-1, No.10.

P-1, No. 6.

Order of Osc.	Grid Potentials in Volts: Calculated from Barkhausen's Equation	Calculated from Scheibe's Equation	Observed	Natural Wave Length
				0.97 cm
Normal	3090	2960	———	
2ND	770	740	———	
3rd	342	330	———	
4th	193	185	———	
5th	123	119	———	
6th	85	82	80	
7th	63	61	———	

P-1, No. 10.

Order of Osc.	Barkhausen's Equation	Scheibe's Equation	Observed	Natural Wave Length
				1.00 cm.
Normal	2870	2750	———	
2nd	720	690	———	
3rd	320	306	———	
4th	188	172	———	
5th	115	110	———	
6th	80	77	83	
7th	59	56	52	
8th	45	43	———	

These may be compared with the values of FP-126.

FP-126 — Grid Potentials in Volts

Order of Osc.	Calculated from Barkhausen's Equation	Calculated from Scheibe's Equation	Observed	Natural Wave Length of Grid 25.2 cm.
Normal	4280	3970	—	
2nd	1070	992	—	
3rd	475	440	385	
4th	268	248	210	
5th	171	159	—	
6th	119	110	—	

The tables show that all the tubes behave in a similar way; namely, only a few of the theoretically possible orders of oscillations can be observed. This is due to the fact that tubes can generate oscillations only in a definite range of grid potentials. The lower limit of this range coincides approximately with the saturation point of the emission current. The upper limit depends upon the temperature of the filament, being higher at the higher temperatures. Also the oscillations of higher orders occur only when the symmetry of arrangement of the electrodes is very good. In the case of FP-126 tubes, the intensity of 3rd order oscillations was very high, being almost comparable to that of the normal waves; but that of the 4th order was considerably lower. This indicates that the symmetry of the electrodes of the FP-126 tube is not very good and explains why oscillations of orders higher than the 4th did not occur. The observed oscillations in the case of our P-1 tubes were of higher orders than those of the tubes FP-126. This means that the symmetry of the electrodes of our small tubes was very much better than that of the FP-126 tubes. The highest grid potential used on the small tubes was 90 volts in order not to over heat the grid. This was why no oscillations of orders lower than the 6th were observed, as these would require a grid potential of more than 100 volts. If in the future filament wires thinner than those used here should become available, we would then be able to heat the filament to higher temperatures without increasing the grid dissipation, and so expect to obtain oscillations of a lower order and therefore of higher intensity with tubes of the same dimensions.

The agreement between the calculated and the observed values is only fair in both the FP-126 and the P-1 tubes. This may be explained by the fact that the constants calculated from the Barkhausen or Scheibe equation do not agree with the constants found experimentally. Further the natural wave lengths of the grids calculated from their dimensions may deviate from the actual values.

Measuring the wave lengths by coupling an outside circuit to the P-1 tube was tried, but no definite result was obtained. In the case of FP-126 tubes, the wave length measurements of the pre-dominating 25.4 cm waves were made by coupling a coil around the tube. The energy picked up by the coil for the higher order oscillations was over twenty times smaller than that for the normal waves, although the plate currents were about the same for both. There was very little or no pick up of energy when the coil was near the tuning Lecher wires. In a more marked extent we would expect this to be true in the case of the P-1 tubes, because the distance from the elements of the tubes to the places where the leads were accessible from outside ~~were~~ was at least two wave lengths long. This distance was only one ~~only one~~ quarter wave length long in the case of FP-126. The most serious difficulty in measuring the wave length was the ~~void~~ lack of sufficient energy of oscillation in the case of P-1 tubes. Although the grid could stand as much as 0.4 watt before it collapsed, the total grid dissipation at the oscillation potentials was less than 0.2 watt. The efficiency is inherently low in retarding field oscillators, and must be much lower in these small tubes at these extreme wave lengths. The amount of power that can be picked up by the coupling coil could be only a small fraction of the radiated energy. Further the glass envelopes of the tubes may absorb more energy at shorter wave lengths. Therefore the energy was not sufficient to be registered in a thermocouple connected to the measuring Lecher wires.

From the above experiments we may conclude that vacuum tubes of very small dimensions give both the normal and higher order oscillations. The characteristics of these oscillations are similar to those found in tubes of larger dimensions. The wave lengths of the normal waves are given approximately by the Barkhausen equation. The energy of the higher order oscillations was very low. The wave lengths were calculated from the dimensions of the grid. The grid potentials where oscillations occur and those calculated from the constants of the tubes agree fairly well. The oscillations of wave lengths of about 1 cm. is practically the shortest limit that can be obtained with the retarding field method.

The author wishes to record his gratitude to Professor G. Potapenko for suggesting this problem and for his advice and assistance in carrying out this investigation.

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