

INVESTIGATIONS IN THE FIELD OF THE ULTRA-SHORT
ELECTROMAGNETIC WAVESI. THE GENERATOR FOR THE PRODUCTION OF
ULTRA-SHORT UNDAMPED WAVES

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(Received November 23, 1931)

ABSTRACT

A description of apparatus for the production of ultra-short undamped electromagnetic waves by the method of Barkhausen and Kurz is given. An investigation has been made of the method of detecting the oscillations by observing the current in the plate circuit of the generator. At a constant plate potential the current is approximately proportional to the amplitude of the oscillations. A comparison of generators with one and with two tubes shows the advantages of the former. In certain cases the energy of oscillations produced by generators with one tube can be considerably increased by a suitable choice of the "ballast" capacity of the generator.

§1. INTRODUCTION

ULTRA-SHORT electromagnetic waves, i.e., waves of the order of a few meters and shorter are acquiring an ever increasing importance in the study of electric and magnetic properties of substances and of their molecular structure. Until quite recently the above investigations were carried out by means of damped oscillations. More reliable results can be obtained using undamped waves.

Methods of obtaining ultra-short waves have been discussed in a considerable number of recently published papers.¹

However the production of waves below 30 cm presents considerable difficulties even at the present time and waves of the order of 10 cm can be obtained only in exceptional cases. Progress is made slowly, due to considerable technical difficulties and to lack of a completely satisfactory theory. All theories suggested up to date, deal mostly with simplified cases and fail to explain the most important details. There is a fundamental difference between the theories of production of long waves and the theory of generation of short waves. In the latter case one has to take into consideration the final velocities of electrons inside of a vacuum tube. Beginning with frequencies of the order of 10^8 per sec., i.e., with waves of the order of 3 m, the period of generated oscillations becomes comparable to the time necessary for an electron to move from one electrode to another. Since the electrons move in the non-uniform field existing inside the tube, the theory presents considerable mathematical

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¹ See for summaries: H. E. Hollmann, *Zeits. f. Hochfr.* **33**, 27-30, 66-74, 101-107 (1929); **35**, 21-27, 76-80 (1930); K. Kohl, *Erg. d. ex. Naturwiss.* **9**, 275-341 (1930).

difficulties. No complete theoretical treatment of the subject is as yet available.

In trying to obtain ultra-short waves we had to keep in mind the shortcomings of the theory of the subject and to take into account experimental data not covered by the present theory. In this respect considerable use was made of our earlier experiments.²

§2. METHODS OF PRODUCTION OF ULTRA-SHORT UNDAMPED ELECTROMAGNETIC WAVES

Undamped electromagnetic waves down to 1 meter can be obtained comparatively easily, using the method of "feed back coupling" well known in radio practice. Using this method K. Kohl³ succeeded in obtaining waves 60 cm long. He worked with vacuum tubes of a special design, the whole oscillating circuit being placed within the tube.

The internal capacity of the tube and the self-inductance of the leads put a limit to a further shortening of the waves. If this method is used the only way of obtaining shorter waves is by separating overtones. C. Gutton and E. Pierret⁴ obtained in this way waves 21 cm long. The low energy of the overtones and the extreme difficulty, almost impossibility, of separating them in a pure state made it necessary to develop new methods.

In 1920 H. Barkhausen and K. Kurz⁵ and independently S. Zilitinkewitch⁶ proposed a new method of obtaining short waves. The method is essentially different from the method of "feed back coupling". Use is made of the electronic oscillations produced when large positive potentials are impressed on the grid with respect to the filament and the plate. Then, under certain conditions, the electrons issuing from the filament will oscillate about the grid as a position of equilibrium.

Assuming for the sake of simplicity plane electrodes H. Barkhausen and K. Kurz computed the frequency of electronic oscillations and the corresponding wave-length λ . It was found to be

$$\lambda = \frac{2000}{(E_g)^{1/2}} \cdot \frac{r_a E_g - r_g E_a}{E_g - E_a} \quad (1)$$

where E_g and E_a are the potentials (in volts) of the grid and the plate with respect to the filament; r_g and r_a are the distances of the grid and plate from the filament. For the case of cylindrical electrodes r_g and r_a will be the radii (in cm) of the grid and the plate.

In case the plate is connected directly to the filament, the potential of the plate can be taken equal to zero. Formula (1) can then be simplified as follows

² G. Potapenko, *Zeits. f. techn. Physik* **10**, 542-548 (1929).

³ K. Kohl, *Phys. Zeits.* **28**, 732-734 (1927); *Ann. d. Physik* 1-62, (1928).

⁴ G. Gutton et E. Pierret, *J. de Phys. et le Rad.* **7**, 15s-16s (1926).

⁵ H. Barkhausen u. K. Kurz, *Phys. Zeits.* **21**, 1-6 (1920).

⁶ S. Zilitinkewitsch, *Drahtl. Tel. u. Tel. (russ)* **18**, 2-22 (1923); **19**, 166-175 (1923); *Arch. f. Electrot.* **15**, 470-484 (1926).

$$\lambda^2 E_g = d_a^2 10^6 \quad (2)$$

where d_a is the diameter of the cylindrical plate or, since for any given tube the right side of the equation is a constant

$$\lambda^2 E_g = \text{Const.} \quad (3)$$

This simple relationship is often called Barkhausen's equation.

In their early experiments made with tubes of the usual type Barkhausen and Kurz obtained waves as short as 43 cm. It was fairly easy to move to a region of still shorter waves. At present the only other successful method of obtaining short waves is by means of magnetic fields which is being developed during recent years.⁷

S. Zilitinkiewitch⁶ and later A. Scheibe⁸ gave more accurate formulae for the wave-length of the oscillations, taking into account the cylindrical shape of the electrodes.

Since at first we shall be interested only in the order of magnitude, we shall use the simpler formulae (1) – (3).

These formulae indicate two possible ways of shortening the wave-length of the generated oscillations. One is by decreasing the dimensions of the tube, i.e., the radii of the grid and the plate. The other—by increasing the positive potential of the grid.

The first method does not lead us very far. In the first place, in decreasing the dimensions of the tube a natural limit is soon reached. In the second place, even before this natural limit is reached the tube ceases to produce oscillations for some, as yet, unknown reason. The second, apparently simpler, method does not lead us very far either. As the grid potential is increased more heating current must be supplied to the filament to maintain the oscillations. F. Tank⁹ has shown that there exists the following relationship between the limiting length of the waves produced by the tube and the emission current required

$$\lambda^3 I_e = \text{Const.} \quad (4)$$

It is seen from the Eq. (4) that a decrease in wave-length calls for a very considerable increase in the emission current, i.e., the heating of the filament. As the heating cannot, of course, be increased indefinitely, the wave-length cannot be shortened beyond a certain limit. Thus A. Scheibe⁸ as a result of his investigation, came to the conclusion that waves of 30 cm were the shortest obtainable by the method of Barkhausen-Kurz.

However, this conclusion could not be considered as final. Several cases were known, at the time we began our investigation, where the wave-length generated was found to be considerably shorter than predicted by Eq. (2).

⁷ See, for example, A. Slutzkin and D. Steinberg, *Ber. d. russ. phys. Ges.* (russ) **58**, 395–409 (1926); *Ann. d. Physik* **1**, 658–670 (1929). A. Zacek, *Zeits. f. Hochf.* **32**, 172, (1928). K. Okabe, *Proc. I. R. E.* **17**, 651–659 (1929); **18**, 1748–1749 (1930).

⁸ A. Scheibe, *Ann. d. Physik* **73**, 54–88 (1924).

⁹ F. Tank, *Arch. sc. Phys. et Natur.* **6**, 320–321 (1924). F. Tank and E. Schiltknecht, *Helv. Phys. Acta* **1**, 110–138 (1928).

Thus, for example, Cl. Schaefer and J. Merzkirch¹⁰ observed an unexpected transition of waves 66 cm long into waves 34 cm long. M. Grechowa¹¹ observed waves 22 and 18 cm long instead of 44 and 36 cm, as expected. Working with a constant grid potential, E. Pierret¹² obtained waves 42 cm and 18 cm long, depending on the length of the oscillating circuit applied to the tube. The observations of A. Scheibe⁸ are of especial interest. He was systematically obtaining waves, whose length was approximately half of the theoretically computed value. These abnormally short waves appeared quite separately from the corresponding longer waves, which proved that the shorter waves could not be considered as the overtones of the longer waves.

Having in view these separate indications of the possibility of obtaining waves of a shorter length than predicted theoretically, we decided systematically to investigate conditions under which such waves appeared and then to attempt to obtain them in as pure a state as possible.

This way of obtaining short waves seemed particularly attractive as it was not necessary to increase the grid potential and the heating current. It was thus possible to operate the tube under more normal working conditions and waves of greater stability could be expected, which in itself is a fact of great importance.

§3. DESCRIPTION OF THE APPARATUS

The fundamental scheme used for the production of ultra short waves is shown in Fig. 1. A vacuum tube V and a "ballast" condenser C of equal capacity were placed between two oscillating circuits: the plate circuit K_a and the grid circuit K_g . The circuits were formed of two copper wires 4.5 mm in

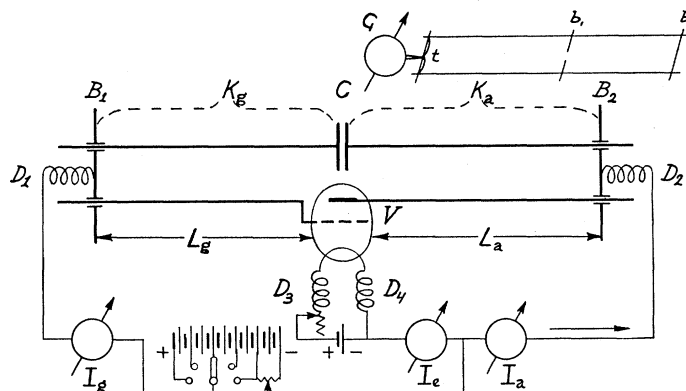


Fig. 1. Schematic diagram of the apparatus.

diameter, with two movable plate bridges B_1 and B_2 . The distance between the axes of the wires was 2 cm. The lengths L_a and L_g of the circuits K_a and K_g could be varied from 5 cm to 75 cm by moving the bridges. The oscillating

¹⁰ Cl. Schaefer u. J. Merzkirch, *Zeits. f. Physik* **13**, 177-178 (1923).

¹¹ M. Grechowa, *Zeits. f. Physik* **38**, 621-634 (1926).

¹² E. Pierret, *C. R.* **184**, 1428-1430 (1927).

circuits were shielded from the rest of the system by means of chokes D_1, D_2, D_3, D_4 .

As seen from the diagram the plate and the filament are connected directly and the potential of the plate was always equal to the potential of the negative end of the filament. The grid voltage E_g was varied from 0 to +720 volts either by means of a d.c. generator and a potentiometer or by means of a battery (400 volts), as shown on the diagram, a switch and small potentiometer P . The latter method is preferable; no high resistance potentiometers are required which when connected in parallel with the grid-plate interval usually leads to errors in the determination of the grid potentials.

As to the various other details, a correct choice of chokes D_3 and D_4 placed in the heating circuit of the tube is of particular importance.

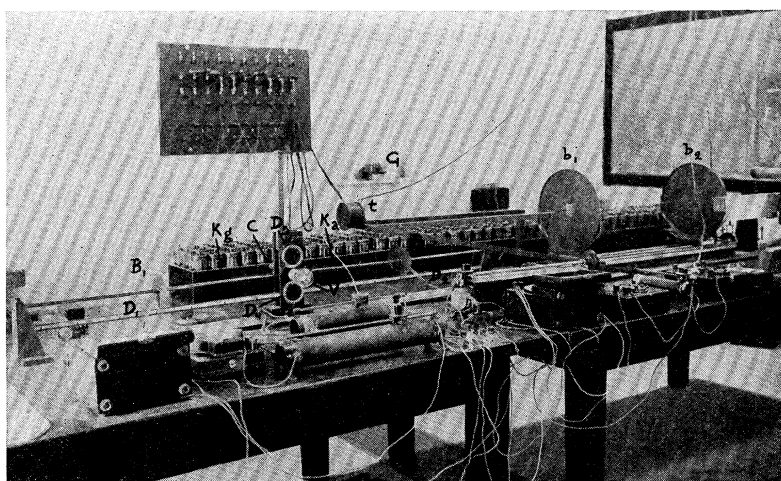


Fig. 2. General view of the apparatus.

A heating current of the order of one ampere passes through these chokes. To avoid the undesirable influence of the magnetic field of this current, it is convenient to make these chokes of two oppositely wound spirals.¹³ As chokes D_3, D_4 had a fundamental wave-length,¹⁴ app. 65 cm, additional chokes of a larger size were placed in the heating circuit when working with waves longer than 50 cm. Chokes D_1 and D_2 are straight spirals of the same dimensions as chokes D_3 and D_4 . They were connected to the outer side of bridges B_1 and B_2 , midway between the wires of the plate and the grid circuits.

The wave-length of the generated oscillations was measured by means of a Lecher system, a thermocouple t and mirror galvanometer G (see Fig. 1). The thermocouple was connected either directly to the bridge of the Lecher

¹³ R. Gunn, Proc. I.R.E. 15, 801-808 (1927).

¹⁴ Each of the spirals used consisted of 14 turns of a copper wire 1 mm in diameter. Radius $r_1=3$ cm, $r_2=3$ mm. When so constructed, the self-inductance and the capacity of the choke were $L=0.36 \times 10^{-6} H$ and $C=0.66 \times 10^{-12} F$ thus giving equal capacitive and inductive resistances for $\lambda=30$ cm.

system,¹⁵ or was placed in an aperiodic circuit, loosely coupled with the Lecher system.

The Lecher system was loosely coupled with the plate circuit. Coupling with the grid circuit was established only in special, specifically mentioned cases.

§4.

It is very important to maintain the heating current of the vacuum tube constant when working with ultra-short waves. When measurements are made at a constant grid voltage a very sensitive and convenient method of controlling the heating current is by means of the emission current. Unfortunately, this method is not applicable when the grid voltage E_g varies. It is known that even within the region of saturation current, the emission current varies appreciably with E_g . Therefore, the steadiness of the emission current with varying grid voltage would indicate variations in the heating current.¹⁶ In our experiments the grid voltage was constantly varying. The heating current was controlled directly by means of an accurate ammeter. The disintegration of the filament could be observed through a change in its resistance or through a change in the emission current at some definite fixed point.¹⁷

Together with the steadiness of the heating current another important feature is the steadiness of the internal "regime" of the tube. It depends largely on the temperature of the tube and on its previous operation. It was found that even a short overheating, resulting in a barely observable disintegration of the filament, has a very great effect on the work of the tube. It may happen that observations made after the overheating will be found in no way comparable with the earlier observations. If observations have to be interrupted for some time, it is found best to "preheat" the tube before beginning a new series of measurements, i.e., to start the heating current some 20–40 minutes before the beginning of measurements. By this time the temperature of the tube comes to a steady value and measurements give comparable results.

§5.

A large number of vacuum tubes have been tested. The following were found most suitable for the production of ultra-short waves: Tubes of the type *R 5* and *J 4* (Russian); of the type *TKD-VT 49* (German); of the type Phillips *E* (Dutch); type *MT 5* (English); and tubes of the type Metal *TMC* and Metal *E 4M* (French). So far we have not been able to obtain good results with any of the American tubes which we had at our disposal.

All the above mentioned tubes have pure tungsten filaments and cylindrical grids and plates. We could observe no ultra-short waves with tubes having plane electrodes or other kinds of filaments.

¹⁵ G. Potapenko, Trans. Phys. Res. Inst. Univ. of Moscow (russ) **6**, 1–103 (1926)—sec. 6.

¹⁶ The importance of complete clearness on this point is seen from a recent discussion: M. J. O. Struth, Ann. d. Physik **4**, 17–32 (1930); **8**, 794–796 (1931); H. E. Hollmann, Ann. d. Physik **5**, 247–260 (1930).

¹⁷ We used as such a point $E_g = 220$ volts and $L = 50$ cm in which no oscillations were produced by the tubes *RS*.

§6. DETECTION OF OSCILLATIONS

The selection of a method of detecting oscillations and of measuring their intensity is one of the most essential questions in all work with ultra-short waves.

In working with a scheme like ours the simplest method of detecting oscillations is by observing the plate current. If the potential of the plate is zero with respect to the negative end of the filament (as it is the case in our scheme), no plate current can appear unless oscillations be present. Its direction will correspond to the flow of electrons toward the plate. Its strength must correspond to the energy or more exactly (as we shall see later) to the amplitude of the oscillations of the plate potential. The plate current is frequently taken as a direct measure of the energy of the oscillations. This assumption is based on the fact that plate current curves are similar to the

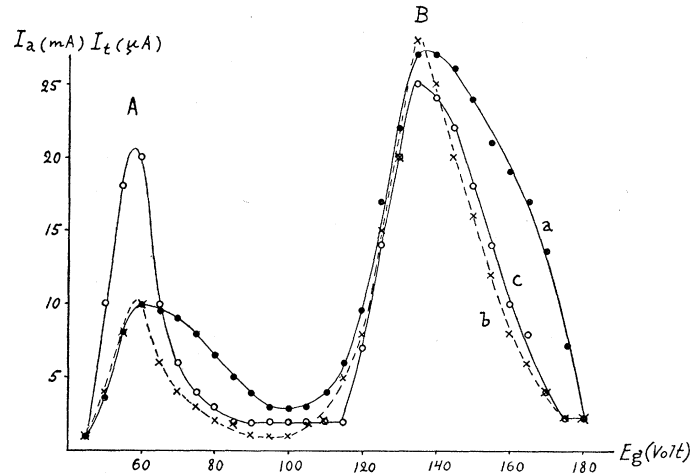


Fig. 3. The curves of the plate current and thermocouple current at $L=60$ cm; heating current $I_h=0.70$ A. (a)—plate current; (b)—thermocouple current; aperiodic circuit at B_1 ; (c)—thermocouple current; aperiodic circuit at the middle of circuit K_a .

curves of the current of a thermocouple placed in the oscillating circuit or in one of the auxiliary aperiodic circuits coupled with the oscillating circuit.¹⁸

In the preliminary experiments simultaneous measurements were made of the plate current and of the energy of oscillations. The latter was determined by means of an aperiodic circuit with a thermocouple. The aperiodic circuit was placed near the bridge B_1 or B_2 (see Fig. 1). Thus it was loosely coupled with the plate or the grid circuits of the tube.

Fig. 3 gives the results of observations. Plate current and thermocouple currents are plotted against the grid voltage at $L_a=L_g=L=60$ cm. There is a similarity between the two curves (curves *a* and *b*).

Their maxima correspond to the same values of the grid voltage. However, there is no strict proportionality between the two curves. After passing

¹⁸ See for example J. Tank and E. Schiltknecht, reference 9, p. 127.

through a maximum the energy of oscillations declines more sharply than the plate current. Analogous results were obtained in all other measurements, with different values of L_a and L_g .

To determine more accurately the relation between the plate current and the thermo current we investigated their dependence on the heating current. A change in the heating current will affect the amplitude of oscillations, hence the plate and thermo currents will also be affected.

Table I gives the results of such measurements, made for two values of L_a and L_g . The grid voltage E_g was maintained at a value corresponding to a maximum of the plate current, which, as we have seen, approximately corresponds to the maximum of the thermo current.

TABLE I. Tube R5 (No. 20).

$L_a = L_g$ (cm)	I_h (amp.)	E_g (volt)	I_a (mA)	I_t (mA)	I_t/I_a	I_t/I_a^2
30	0.700	100	2.5	30.0	12.0	4.8
30	0.690	106	2.2	24.0	11.0	5.0
30	0.680	115	1.85	18.8	10.2	5.5
30	0.670	123	1.3	12.0	9.2	7.1
30	0.660	130	1.0	7.9	7.9	7.9
30	0.650	128	0.35	1.0	3.0	8.3
24	0.700	142	2.5	24.0	9.6	3.8
24	0.690	152	2.2	18.8	8.5	3.9
24	0.680	153	1.65	12.8	7.7	4.2
24	0.670	158	1.15	7.5	6.5	5.7
24	0.660	163	0.45	1.2	2.7	6.0

Table I shows that a change in the heating current produces similar changes in the plate and thermo currents.

The last two columns of Table I give the values of the ratios I_t/I_a and I_t/I_a^2 . It is seen that the ratios vary with the heating current. The two columns vary in opposite directions. However I_t/I_a varies about three times faster than I_t/I_a^2 . Thus, strictly speaking, the plate current is proportional neither to the energy of the oscillations, nor to their amplitude. It corresponds, however, more closely to the amplitude of the oscillations. The above measurements were made at a constant plate voltage. So we may say: *when the plate voltage is kept constant, the plate current may be taken as approximately proportional to the amplitude of oscillations.* In our case the plate was connected directly to the filament and the above restriction was automatically satisfied. It is clear that when the plate voltage varies we cannot expect any correspondence between the plate current and the amplitude of the oscillations.¹⁹ It is obvious that we shall have plate current at any positive plate potential, even in the absence of oscillations. Conversely, there will be no plate current of the direction we consider, when the plate has a sufficiently large negative potential, i.e., when its absolute magnitude will be greater than the amplitude of the oscillations.

¹⁹ Comp. W. Kroebel, Zeits. f. Physik **61**, 242 (1930).

§7.

The plate current is only an approximate measure of the energy of oscillations. It is very convenient to use, however, as it is hundreds, even thousands of times, greater than the current from the thermocouple. In our measurements we used the plate current. The thermo current was measured only when the plate potential had to be changed.

Erroneous results are frequently obtained when working with an aperiodic circuit and a thermocouple. If the aperiodic circuit be removed from the bridge and brought near the middle of the oscillating circuit, instead of the curve *b* we obtain curve *c* Fig. 3 giving an entirely different idea of the relative intensity of oscillations in regions *A* and *B*. This is due to the fact that oscillations *A* and *B* had a different wave-length ($\lambda \sim 100$ cm and $\lambda \sim 60$ cm). Moving the aperiodic circuit brings it near the loop of the first wave and the node of the second one. The maximum of the first wave was thus increased. Hence, to obtain correct results when measuring the energy of waves of different length, the aperiodic circuit must be kept in a fixed position with respect to the nodes and loop of the waves.

In our experiments the aperiodic circuit was placed near one of the bridges. It would seem to be preferable to place the thermocouple (or detector) directly in the bridge, as was done by E. Gill and J. Morrell²⁰ and H. Hollmann.²¹ However, the sensitivity of this method depends greatly on the resistance (capacitance) of the bridge, which may vary considerably with the wave-length as we are near one of its fundamental periods when working with waves within the range of 10–100 cm.

The grid current I_g can also be used for measuring the intensity of oscillations. We have

$$I_a + I_g = I_e. \quad (5)$$

The emission current I_e varies little within the saturation region (where we worked) and at constant heating current. From the Eq. (5) it is seen that as the plate current varies, the grid current must vary in an opposite direction. The plate current, however, seldom exceeds 15 percent of the grid current. Variations in the grid current are much harder to observe.

When the intensity of oscillations is low, it becomes extremely difficult to observe variations in the grid current. In our work, measurements of the grid current were made only in very rare cases.

§8. GENERATOR WITH ONE AND TWO TUBES

In a scheme like ours, where the tube *V* is paired with a condenser *C* of equal capacity (see Fig. 1) it would seem natural to replace the condenser with another vacuum tube and to operate the two tubes simultaneously. The resulting scheme would be equivalent to the one proposed by F. Holborn²² for the production of short waves by the method of feed back coupling. M. T.

²⁰ E. Gill and L. Morrell, *Phil. Mag.* **44**, 161–178 (1922).

²¹ H. E. Hollmann, *Ann. d. Physik* **86**, 129–188 (1928).

²² F. Holborn, *Zeits. f. Physik* **6**, 328–338 (1921).

Grechowa²³ and E. Pierret²⁴ used this scheme for the production of short waves by the method of Barkhausen-Kurz. The latter found that: (1) in the presence of a second tube the oscillatory energy is more than doubled²⁵ and (2) if there is a slight difference in the length of waves produced by each tube when working separately, they will produce, when working together, waves of only one length. The wave-length will be shorter than that produced by each tube separately.

In the beginning of our investigation we tried to use this scheme. We soon discovered the difficulty of finding two tubes with similar properties. Several hundreds of tubes of the type R5 were tested and only 4 or 5 were found

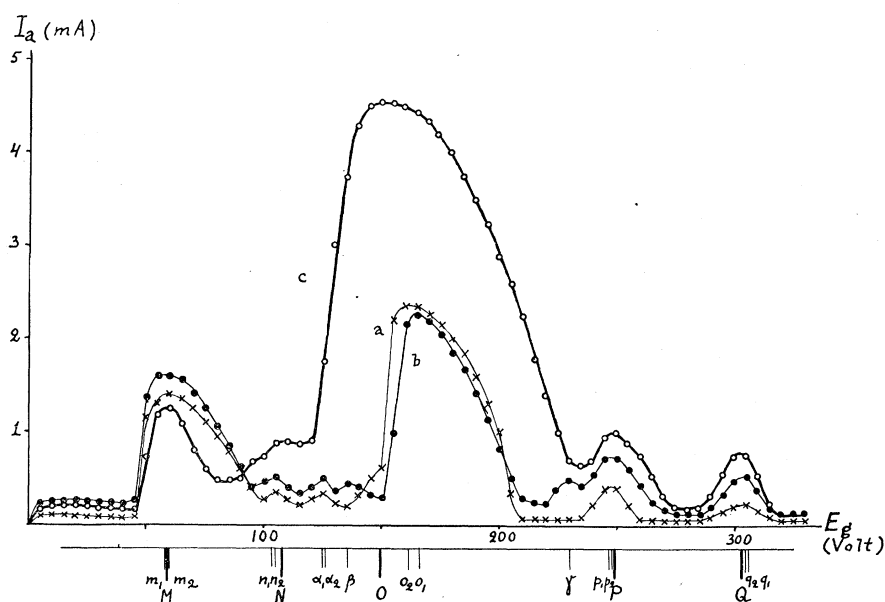


Fig. 4. (I_a, E_g)-Characteristics at $L=50$ cm; $I_h=0.70$ A. (a)—Vacuum tube No. 20, “ballast” tube No. 5. (b)—Vacuum tube No. 5, “ballast” tube No. 20. (c)—Vacuum tube No. 20 and No. 5 working simultaneously.

whose characteristics were similar with respect to the number of regions of oscillations, their location and the energy of oscillations.

Fig. 4 shows the relation between the plate current and the grid voltage for two such tubes (Nos. 5 and 20). When one tube was lighted the other was used merely as a condenser C (see Fig. 1). Such curves will be called the (I_a, E_g)-characteristics.

The lengths of the plate and grid circuits and the heating current were always kept constant, while these curves were obtained. Fig. 4 shows also the (I_a, E_g)-characteristic for the two tubes working simultaneously. It is seen

²³ M. T. Grechowa, Trans. Electr. Res. Inst. (russ) 11, 10–18 (1925); Zeits. f. Physik 35, 50–58 (1925).

²⁴ E. Pierret, reference 12.

²⁵ See also A. Scheibe, Jahrb. dr. Tel. u. Tel. 27, 1–5 (1926).

that this characteristic is not a sum nor a definite function of the individual characteristics of the two tubes. In the regions N and O the energy of oscillations is greater than the sum of the energies of the individual oscillations n_1, n_2 and o_1, o_2 respectively. In the region M the oscillatory energy is considerably less than each of the energies m_1, m_2 . Finally in the region P the total oscillatory energy barely exceeds the energy of individual oscillations P_1 and P_2 .

Hence E. Pierret's first conclusion cannot be extended to all cases of such oscillations. The same may be said of his second result. With two tubes working simultaneously, the wave-length obtained was shorter or longer than the wave-length produced by one tube. When the characteristics of the two tubes differed more than those shown in Fig. 4, the resulting oscillations consisted of waves of two or more frequencies. Fig. 5 gives (I_a, E_g) -characteris-

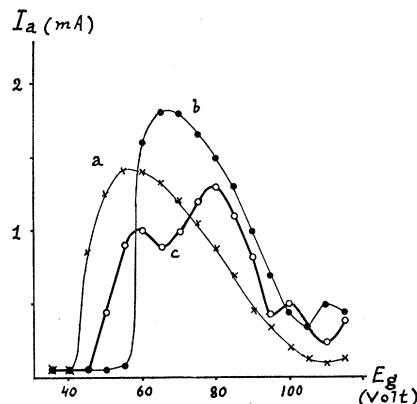


Fig. 5. (I_a, E_g) -characteristics at $L=50$ cm; $I_h=0.70$ A. (a)—Vacuum tube No. 20 “ballast” tube No. 16. (b)—Vacuum tube No. 16 “ballast” tube No. 20. (c)—Vacuum tube No. 20 and No. 16 working simultaneously.

tics for a pair of tubes differing more than tubes No. 20 and No. 5. There is no regularity of any sort in the addition of the oscillations. It is seen that the resulting energy of oscillations produced by two tubes is less than the energy produced by each tube separately. This was the case for region M on Fig. 4.

The curves of Fig. 4 show that the resulting (I_a, E_g) -characteristic for the two tubes is lacking in finer details which are seen on the characteristics of single tubes. In fact, regions $\alpha_1, \alpha_2, \beta, \gamma$ are so to speak “absorbed” by region O , as is seen on Fig. 4. Preliminary work had shown, however, that in the study of oscillations these small regions of low energy are of particular interest. Accordingly, it has been decided to use only one tube for the production of oscillations. This tube was balanced against a small condenser of variable capacity, or against another tube of the same type and of equal capacity. This second tube was used as a condenser. It was not lighted during the experiments. We shall call it a “ballast” tube.

§9. THE "BALLAST" CAPACITY

The capacity of the condenser C (see Fig. 1) or of the "ballast" tube must be as nearly equal to the capacity of the working tube as possible. It is not sufficient to have a "ballast" tube of the same type as the working one. Two tubes of the same type may differ in capacity by as much as 10–15 percent. Fig. 6 shows the effect of such a difference in capacity on the operation of the generator. It shows four (I_a, E_g) -characteristics of the tube of type R5.

One of the characteristics is obtained by using as "ballast" tube, No. 18, of similar type. The second characteristic was obtained with another "ballast" tube, No. 6, of a similar type. The first characteristic is very similar to the one when tube No. 20 was paired with tube No. 5 (see Fig. 4). The second characteristic shows a total absence of oscillations in the region 0.

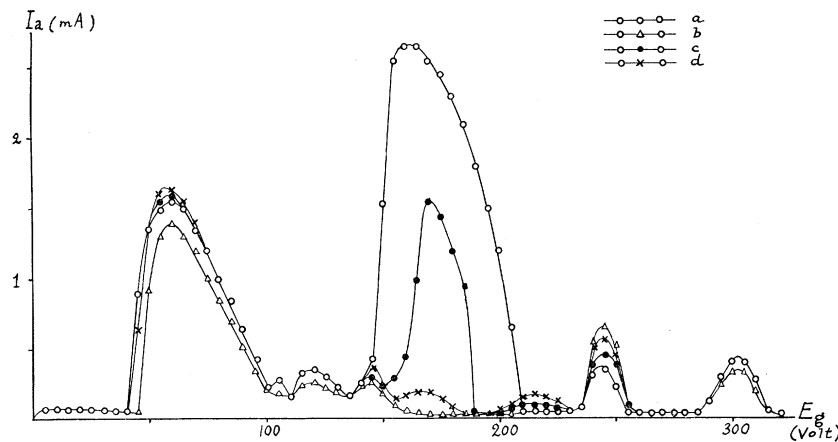


Fig. 6. (I_a, E_g) -characteristics at $L = 50$ cm; $I_h = 0.70$ A (a)—Vacuum tube No. 20, "ballast" tube No. 18. (b)—Vacuum tube No. 20, "ballast" tube No. 6. (c)—Vacuum tube No. 20, "ballast" tube No. 18 + Capacity 0.12 cm. (d)—Vacuum tube No. 20, "ballast" tube No. 18 + Capacity 0.18 cm.

It was found that tube No. 6 had an internal capacity approximately 0.2 cm greater than the other tubes.²⁶

To prove that the change of characteristics was really due to the difference in capacity, a small condenser of variable capacity was connected between the plate and grid circuits at the tube No. 18, in parallel with its plate-grid capacity.

Two of the characteristics of tube No. 20 taken with this condenser are shown in Fig. 6. The first one, taken with the condenser capacity $C_1 = 0.12$ cm, shows a considerable decrease of oscillatory energy in the region 0. The second characteristic, taken with the condenser capacity $C_2 = 0.18$ cm, shows almost a complete absence of oscillations in region 0. The characteristic is very similar to that of the pair of tubes No. 20–6. At the same time we

²⁶ The capacity of tubes Nos. 5, 18, 20 measured at $\lambda = 1$ m was 2.85–2.9 cm, the capacity of tube No. 6, 3.1 cm.

observe an increase in the intensity of oscillations in the region P , and no changes in regions M and Q .

This difference in the effect of the presence of the condenser on different regions can be explained from a consideration of the distribution of the loops and nodes of the standing waves in the plate and the grid circuit. Fig. 7(a) shows the distribution of potential for the region M , Fig. 7(b) and 7(c) for the region O . It is seen that when the loops are not situated in the immediate neighborhood of the tubes (region M) a small difference in their capacity has a small effect on the characteristic.

When, on the other hand, the loops are in the neighborhood of the tubes (region O) a difference in capacities has a very pronounced effect on the standing waves and the energy of the oscillations falls off sharply.²⁷

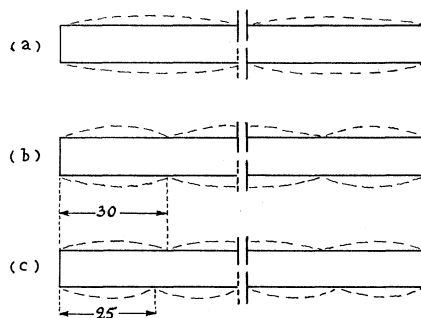


Fig. 7. Distribution of the potentials in the plate and the grid circuits. Vacuum tube No. 20 at $L = 50$ cm. (a)—Region M , ballast tube No. 18 or No. 16. (b)—Region O , ballast tube No. 18. (c)—Region O , ballast tube No. 18 with condenser 0.18 cm or ballast tube No. 6 without condenser.

The above considerations show the importance of having the capacity of the “ballast” tube equal to that of the working tube.

Obviously, the working and the “ballast” tubes must have sockets of equal capacity. This can easily be checked by interchanging the positions of the working and the “ballast” tube. If the capacities of the sockets are equal such an interchange will produce only an insignificant change in the characteristic.

In conclusion the author wishes to express his thanks to the Rockefeller Foundation for the grant of a Fellowship and to Professor R. A. Millikan for the facilities of the Norman Bridge Laboratory.

²⁷ Under such circumstances oscillations are produced such that a second wave train is superimposed on the one already present. For this second train $\lambda^2 E_g$ is below the usual value. The above refers to oscillations which in future articles we shall call normal oscillations.

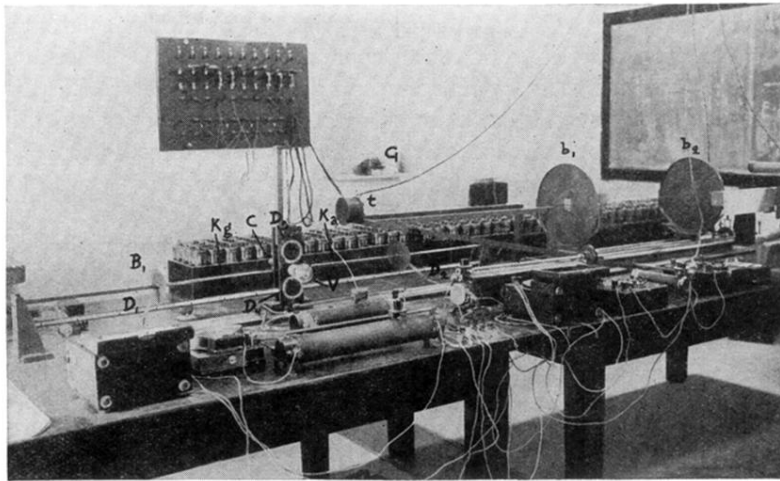


Fig. 2. General view of the apparatus.