# The Discharge Through Rarefied Gases under the Influence of High Frequency Currents.

By

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## Part I. Introduction.

The phenomena of electric circuits through gases, when the wave forms of the electric source have various kinds of shapes and various time durations, must be very complex, but the investigation of them is very important and interesting from the standpoint, not only of a pure theoretical investigation of gas discharge phenomena, but of its technical applications as well.

The first step towards the future investigation of discharge phenomena under such conditions, treated here in this paper, is to observe electric circuits through rarefied gases under the influence of undamped high frequency currents.

The references with regard to this same problem are not rare, but the results, under various conditions according to various investigators, are not always in coincidence.(1) The phenomena, in spite of the many important investigations of these authors, are still in an obscure state.

The discharge phenomena of low pressure gases, as it is well known, are very different according to the current density, or owing to the power supplied to the discharge cirsuits, even under the same gas pressure. Moreover, when the frequency is high enough, special phenomena, characteristic to the high frequency discharges, must themselves appear.

It has been found that the discharge under high frequency currents, under favourable conditions, occurs in three stages, in a successive sequence. They are called, for simplicity, discharges of type A, type B and type C.

Type A is, a characteristic discharge for high frequency currents occurring from the same principles as the so-called electrodeless discharge.[2] Its luminosity consists of one colour, and, under certain conditions, it can be obtained in the space between the electrodes, and separated from them as if it were a luminous floating ball, without practically any luminosity at the electrodes. Some typical ones are shown in Fig. (1).

Type A.

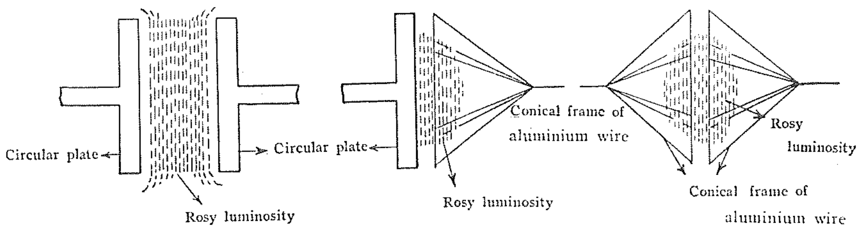


Fig. 1.
Discharges in an Air Vessel.

Type B can be called a "Townsend Discharge"[3] in low gas pressures, just as it was so called by R. Seeliger and J. Schmekel in the case of a d.c. discharge. This type of discharge in low gas pressures occurs not only under high frequency currents but also under a.c.s. of 60 cycles and under a d.c. as well, when the discharge currents are limited. Under certain favourable conditions, a diffused luminosity starts from the anode and spreads in the space between the electrodes, and also as far as to the negative electrode, when more current is allowed to flow.

Type C is a usual glow discharge, having a cathode layer, Crooke's dark space, negative glow, Faraday's dark space, positive column and positive glow etc.

Using a large air discharge vessel and sphere electrodes, plate electrodes and others of special forms, experiments were tried to see whether the above three types would occur in a successive sequence. The pressure was about 2–3 milimetres of Hg or more. The diameters of the spheres and plates were about 5 cms., and the electrode distances were less than 2–3 cms.

In the course of striking, when the terminal voltage was increased gradually, under favourable conditions, types B and C appeared in a successive sequence. But it was impossible to make type A appear at first. When the terminal voltage was decreased gradually, after type C had been once initiated, type A remained.(4) But by using a neon glim lamp of a beehive type, of which one electrode was a plate disc, it was found that the above three types of discharges occurred in a successive sequence, when the voltages was increased, and as well when it was decreased. It was also found that the order of appearance of types A and B changed according to the frequency and to other conditions, type C always being last in striking. Therefore using a neon glim lamp, their characteristics in detail were investigated.

## Part II. Experiments and their Results.

As an electric source, a valve oscillator of variable frequencies was used. As an output circuit, a resonance circuit was used, which was very loosely coupled magnetically to the oscillator circuit. A discharge gap under test was connected across its variable condenser terminals. The terminal voltage was measured by a valve crest voltmeter. The electrical connections are as shown in Fig. (2) and in Fig. (3). The oscillator was kept at a certain constant condition of a certain constant frequency,

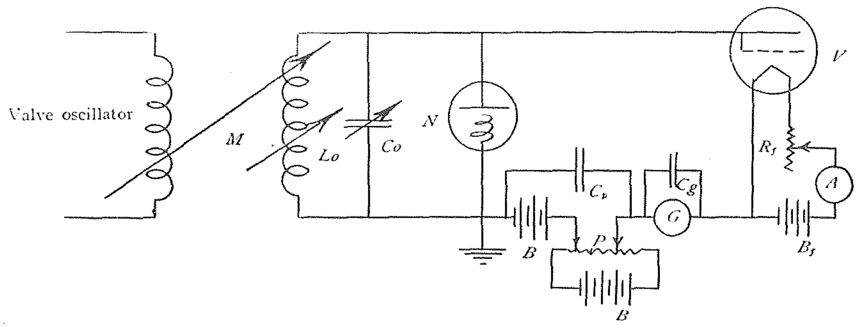


Fig. 2.

Electrical Connections for pure A. C. S.

N: A neon lamp under test.
Lo, Co: Inductance and capacity of the output circuit.
P: Potentiometer. V: 3-electrode valve.
G: Galvanometer. Cp: Condenser of about 3 u.f.s.
A: D.C. ammeter. Cg: Condenser of about 3 u.f.s.
Bf: Filament battery. Rf: Filament resistance.
B: Battery.

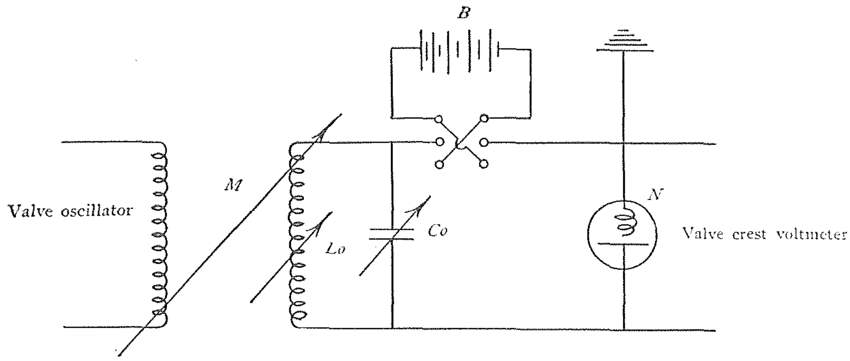


Fig. 3.
Electrical Connections for an A.C. Superimposed on a D.C.

and the terminal voltage across the discharge gap was varied by varying the condenser in the resonance circuit.

First, using a.c.s. of various frequencies, then a.c.s. of a constant frequency superimposed upon a d.c. of various voltages, and at last a.c.s. of various frequencies superimposed upon a d.c. of a certain constant voltage, there were measured the corresponding minimum striking voltages, $E_1$ s, of the above three types of discharges, and also there were measured the minimum voltages, $E_2$ s, that could maintain the discharges after they had been once initiated. Varying the condenser of the output circuit, the terminal voltage was increased until the discharges were initiated, and after they had once been initiated, the voltage was then decreased, and it were found the minimum voltages that could maintain the discharges.

The degree of the coupling and the relative magnitude of the inductance and capacity of the resonance circuit were found to have some effects upon these voltages, but in spite of it, the general tendencies were the same.

The neon glim lamp under test was of 220 volts and 5 watts. And its statical sparking and extinction voltages were about 164 volts and 134 volts respectively.

(1) Discharge Pehnomena under the Influence of Undamped High Frequency Currents.

The Discharge phenomena changed according to the frequency as follows:

(a) $f=0.40\times 10^6$ cycles per sec.

When the terminal voltage was increased to 170 volts, the surface of the electrodes were covered by a feeble diffused orange luminosity. This is a discharge of type B. As the voltage was further increased, the luminosity spread out in the space between the electrodes, its colour becoming deeper, and, at last, at 189 volts the glow adhered closely to the disc as well as to the spiral electrodes. This is a discharge of type C. But in the case of the neon glim lamp under test, there appeared neither the positive column nor the positive glow. The negative glow was orange. Then the terminal voltage was decreased. At 181 volts, type C was extinguished, but the surfaces of the electrodes were still covered by a diffused orange luminosity. As the voltage was decreased further, the glow became fainter, and, at 168 volts, it disappeared.

(b) $f=0.945\times 10^6$ cycles per sec.

When the terminal voltage was increased, at 140 volts, a luminous column, its colour being feeble orange tinged with violet, appeared in the space between the electrodes, while both electrodes remained practically without luminosity. This is a discharge of type A. As the voltage was increased further, this luminous column became larger, and, at 171 volts, a diffused luminosity appeared around the surface of the electrodes. This is a discharge of type B. As the voltage was increased further, at 184 volts, the negative glow adhered closely to the plate electrode, and, at 195 volts, to the spiral electrode as well. The voltage was then decreased. At 170 volts type C disappeared, but types B & C still remained. At 158 volts, type B disappeared, type A still remaining. At 131 volts, type A also disappeared.

(c) $f = 2.63 \times 10^6$ cycles per sec.

The phenomena in this case was almost like those in the case of (b), except a little difference in the course of transition from type B to type C. At 124 volts, at first, a luminous column appeared. But in this case, the column was more compact and appeared more abruptly than in the case of (b). At 164 volts, type B appeared, and, at 173 volts, the negative glow adhered to the plate electrode. But in this case, from the luminous column, through the space between the neighbouring layers of the spiral, to the space between the spiral electrode and the glass wall, a pretty luminosity of a special form appeared. It began from the luminous column, where its colour is feeble orange, tinged with violet, and runs through the space between the neighbouring layers of the spiral, where its colour becomes deeper, and ends at the space between the spiral electrode and the glass wall, its colour, there, being violet. As the voltage was further increased to 193 volts, the spiral electrode was also covered closely by the negative glow and the special luminous form disappeared. As the voltage was, then, decreased, just the reverse sequence followed. At 174 volts, only the luminous column remained, and, at 85 volts, at last, it also disapppeared. The sequence in this case was as shown in Fig. 4.

Having found, thus, the general tendency of the discharge of the lamp under test, then, there was investigated systematically, how the minimum striking voltages, $E_1$ s, and also those which could maintain the discharges when they had been once initiated, $E_2$ s, changed according to various frequencies. The result obtained is as shown in Figs. 5, 6 and 7.

The $E_{A1}$, $E_1$ of type A decreases as the frequency increases. The higher the frequency, the lower the voltage at which it appears. The luminous column became more dense and appeared more abruptly as it had a certain inertia, as the frequency was increased. It appears at 109 volts at the frequency of $5.09 \times 10^6$ cycles per sec., and at 159 volts at the

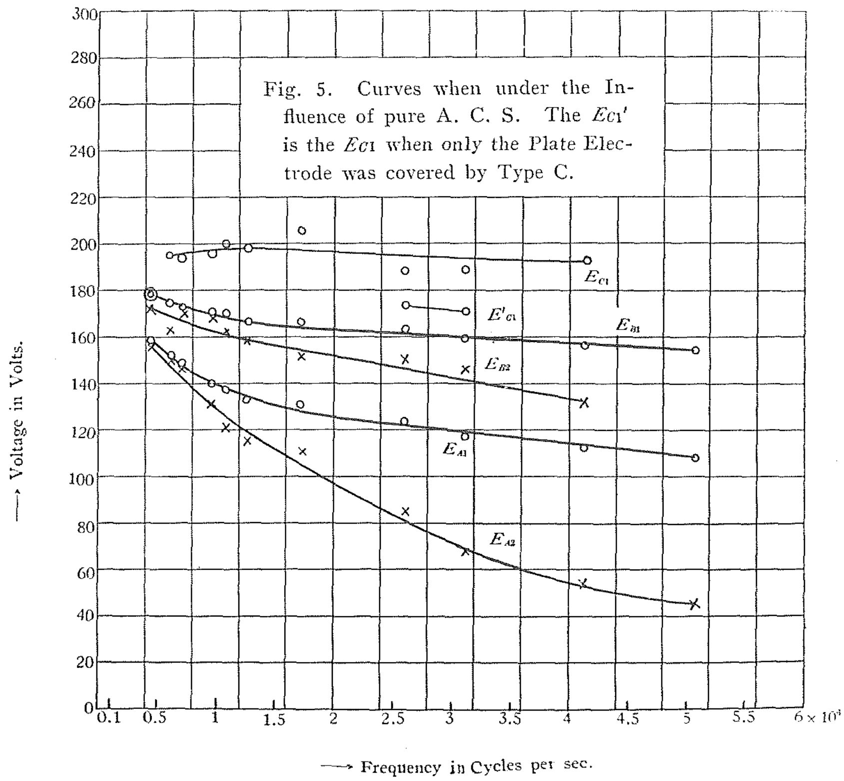


Fig. 5. Curves when under the Influence of pure A. C. S. The $E_{C1}'$ is the $E_{C1}$ when only the Plate Electrode was covered by Type C.

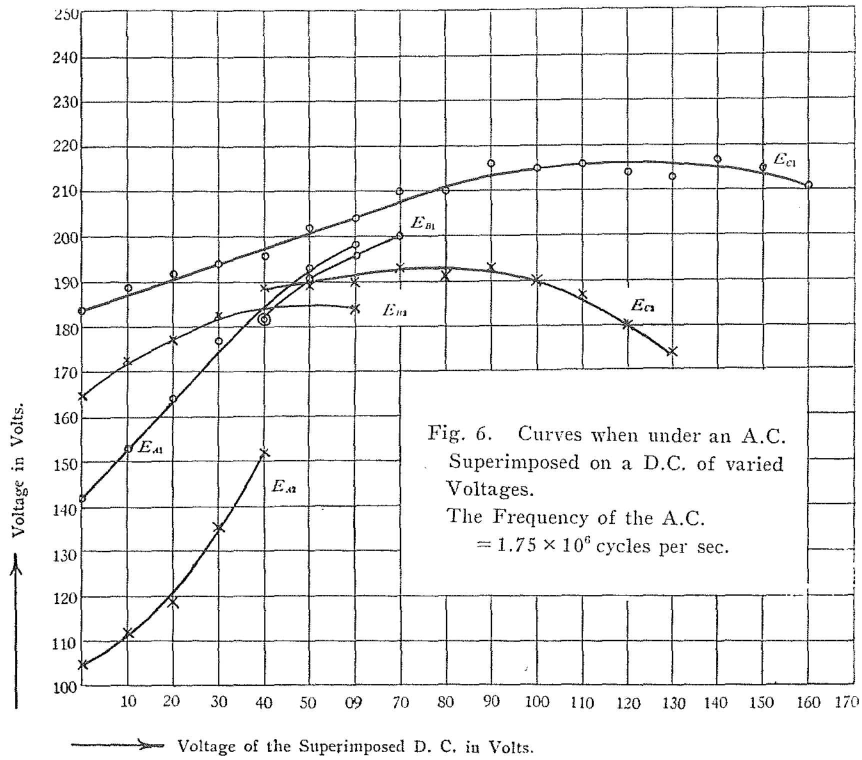


Fig. 6. Curves when under an A.C. Superimposed on a D.C. of varied Voltages.
The Frequency of the A.C. $= 1.75 \times 10^6$ cycles per sec.

frequency of $0.435 \times 10^6$ cycles per sec., while the statical sparking voltage of the lamp is about 164 volts. The $E_{B1}$, $E_1$ of type B follows the same tendency: It decreases as the frequency increases. It is 155 volts at $5.08 \times 10^6$ cycles per sec., and 179 volts at $0.435 \times 10^6$ cycles per sec. As to the $E_{C1}$, there could not be obtained reliable results. The reason was that the negative glow adhered to the electrodes very irregularly owing to the change of the frequency. Discharges of the types A and B, having occured before, may affect type C, and the transion point from type B to type C was not very distinct, and, moreover, as the electric source, in this experiment, was not powerful enough, this discharge could not be initiated without making the coupling too close to get reliable results. The degree of coupling and magnitude of the capacity of the output circuit affected considerably in the course of the striking of type C. It is also feared that the peculiar natures of the neon lamp itself affected type C considerably.

The $E_{B2}$, $E_2$ of type B, decreases as the frequency increases. It is 132 volts at the frequency of $4.15 \times 10^6$ cycles per sec., and 173 volts at

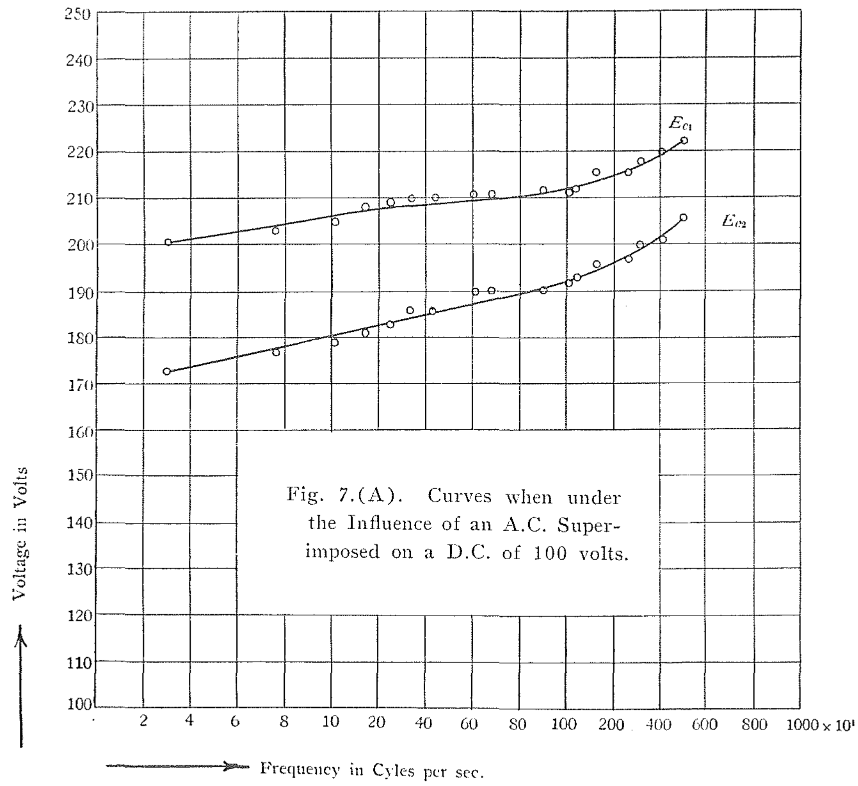


Fig. 7.(A). Curves when under the Influence of an A.C. Superimposed on a D.C. of 100 volts.

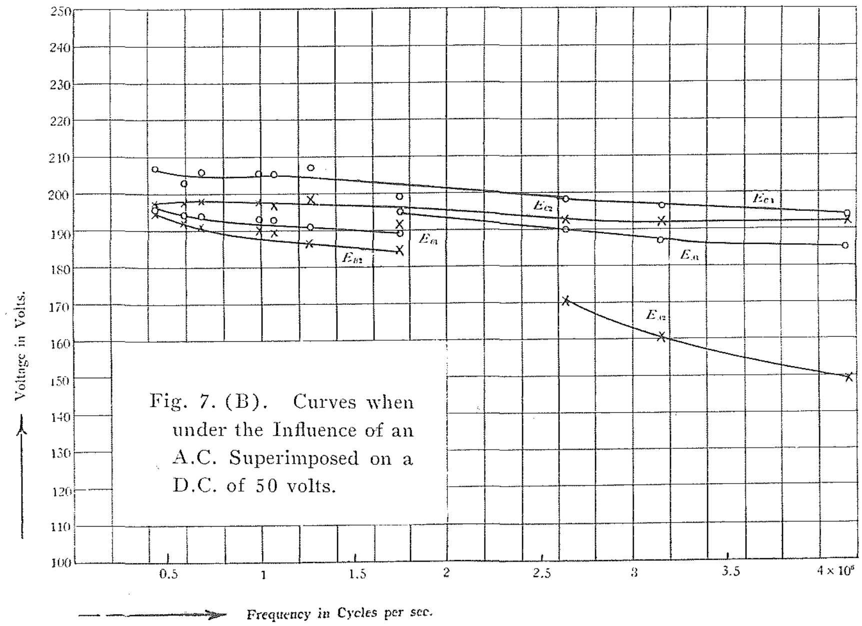


Fig. 7. (B). Curves when under the Influence of an A.C. Superimposed on a D.C. of 50 volts.

the frequency of $0.435\times10^6$.. That of type A decreases, also, as the frequency increases, being 46 volts at the frequency of $5.08\times10^6$ cycles per sec., and 157 volts at $0.435\times10^6$ cycles per sec.. If there is taken the difference between these two kinds of voltages $E_{A1}-E_{A2}$, it is found that it increases as the frequency increases, being 53 volts at $5.08\times10^6$ cycles per sec., and 1 or 2 volts at $0.436\times10^6$. That means that the difference of the power to initiate type A and that to maintain it will be larger as the frequencyy increases. As to the difference of these two voltages for type B, almost the same tendency is found to exist.

(2). Discharge phenomena under the Influence of Undamped High Frequency Currents Superimposed on a D.C.[5]

In order to investigate how the wave forms of the voltage may have an affect on the nature of discharge, there was used as an electric source an a.c. superimposed on a d.c.. First, the frequency of an a.c. being kept constant, the voltage of the superimposed d.c. was varied. Then, the voltage of a d.c. being kept constant, the frequency of the superimposed a.c. was varied.

(A) The case, when the Frequency of an A.C. being kept constant, the Voltage of the Superimposed D.C. was varied.

The general discharge phenomena, in this case, were as follows.

When the voltage of the superimposed d.c. was considerably large, there could not practically be obtained the discharges of types B and A, but of type C only:[6] As the a.c. voltage was increased, by varying the condenser, at a certain voltage, type C appeared abruptly, but neither that of B nor C could be found. In this experiment, as the plate was used as a negative electrode, it was closely covered with a negative glow. When the voltage of the superimposed d.c. was 150 volts, the lamp was not extinguished. But when it was 130 volts or less, the negative glow, adhering closely to the negative electrode, became smaller in area and fainter in colour as the voltage was decreased, and, at last, at a certain voltage it abruptly disappeared.

When the voltage of the superimposed d.c. was small, the phenomena was quite different. When it was 60 volts, at the terminal resultant voltage of 196 volts, type B appeared at first. At 198 volts, type A appeared, and at 204 volts, the negative glow adhered closely to the negative electrode. Then the terminal voltage was decreased, and, it was found, that at 190 volts, type C disappeared, type B still remaining. At 184 volts the latter disappeared. When the voltage of the superimposed d.c. was 30 volts, at 177 volts (terminal voltage), type A appeared, and on further increasing the terminal voltage, type B soon appeared, and these two became stronger as the voltage was increased. At 194 volts a negative glow adhered closely to the plate electrode. Then the voltage was decreased. At 183 volts type C disappeared, and, at about the same time, type B also disappeared, type A alone remaining. At 135 volts, it also disappeared. The results are as shown in Fig. 6. The results are summarized as follows:

When the voltage of the superimposed d.c. was less than about 60 volts, type A appeared. Its striking voltage, $E_{A1}$, became smaller as the superimposed d.c. decreased. Type B appeared almost in the same range. Its striking voltage also became smaller when the superimposed d.c. decreased. But the order of appearance of types A and B was reversed. At 60 volts, of the superimposed d.c., type B appeared first and then type A, but at 30 volts, type A first and then type B. As to the results of type C, regular ones could not be obtained. But the general tendency was that the $E_{C1}$ became smaller as the superimposed d.c. became less.

The $E_{B2}$ and $E_{A2}$ became smaller as the superimposed d.c. was decreased.

(B) The Case, when, the Voltage of the Superimposed D.C. being kept constant, the Frequency of the A.C. was varied.

The general tendency was as follows:—

When the voltage of the superimposed d.c. was pretty large, say, 100 volts, type C only was observed. When it was small, say, 50 volts, however, the phenomena were more complex. In the latter case, at the frequency of $1.74\times10^6$ cycles per sec., or more, type A occurred at first, and then types B and C appeared, almost at the same time. When the voltage was decreased, types B and C disappeared first, at almost the same time, and then type A. At the frequency of $1.26\times10^6$ cycles per sec., or less, type B appeared first and then type C, type A, in this case, being not seen at all. This order of appearance of types A and B was reversed, in this case also, owing to the change of the frequency. The results are as shown in Fig. 7.

The Case when the Superimposed D.C. was 100 volts.

The $E_{C1}$, $E_1$ corresponding to type $C$, in this case, increases as the frequency increases. It is 201 volts at $3.0\times10^4$ cycles per sec., being about 40 volts higher than the statical sparking voltage, and 226 volts at the frequency of $5.08\times10^6$ cycles per sec.

The $E_{c2}$ increases as the frequency increases, and is 177 volts at the frequency of $3.0 \times 10^4$ cycles per sec., being about 10 volts higher than the statical sparking voltage, and 206 volts at the frequency of $5.08 \times 10^6$ cycles per sec.

The Case when the Superimposed D.C. was 50 volts.

The $E_1$s for all the three types, A, B and C have the same tendency: they decrease as the frequency increases.

This is the same tendency for the $E_2$ s also. When the frequency is high enough, type A appears first as the voltage is increased, and remains to the last as it is decreased. But at lower frequencies, type A cannot be seen, and type B appears first as the voltage is increased, and remains to the last as it is decreased.

(3) The Discharge of Special Forms.

By using a neon glim lamp, whose electrodes are of special forms, it was found that, under favourable conditions, a pretty luminosity of a special form appeared as shown in Fig. 4. This is manifestly, owing to the special electrode forms. It appeared when negative glow adhered closely to the plate electrode, while the spiral electrode was not yet adhered to by it. If the terminal voltage was increased further, until the spiral electrode also adhered to by the negative glow closely, it disappeared. The sequence of its formation is as follows: As the terminal voltage is increased, type A usually appears first in the space between the upper surface of the plate electrode and the spiral, and often at the same time, also in the space between the lower surface of the plate electrode and the spiral, and as the voltage is further increased gradually, both parts spread, and in the space between the spiral electrode and the glass wall, there appears a diffused violet luminosity as shown in Fig. 4. The luminosities in the inner and outer space of the spiral electrode spread gradually as the voltage is further increased, and, at a certain stage, they unite together, in the space between the neighbouring layers of the spiral, and, thus, form a special shape. The colour in the inner and outer spaces of the electrode, is violet tinged with a faint orange, but its stem part between the layers of the spiral, is a rather deep orange tinged with violet. This special shape of luminosity, it is supposed, is owing to the special electrode forms, and, not necessarily due to the kind of filled gas: Almost the same shapes can be formed as well in a large air vessel with the pressure of 2–3 millimeters of $Hg$, using the same electrodes in it, after having broken the glass wall of the lamp.

In the air vessel, the luminosity at the top and bottom parts is light blue, and at the stem part it is rose coloured. It was also investigated how the circuit constants affected the formation of such forms of discharges and the following results were obtained.

The Effects of a Resistance, Inductance and Capacity.

There was put a series water rheostat ranging from 400 ohms up to 2 megohms, a self inductance, and an air condenser ranging from 10 $\mu.\ \mu.$ F.s. up to 500 $\mu.\ \mu.$ F.s., and, thus, were measured the corresponding lowest frequencies which made such forms to appear. The effects of them are different depending upon whether they are put between one terminal of the condenser and the spiral electrode, or placed between the other terminal and the plate electrode. In the former case, the larger the resistance, the larger the inductance, but when the capacity was smaller, at the lower frequncies, then, special shapes appeared. In the latter case, it was, always, difficult for them to appear.

The Effect of Polarity etc.

There was used, as an electric source, an a.c. superimposed on a d.c., and, the influence of polarity on the special forms was investigated. When the spiral electrode was connected to the positive terminal of the battery, the figures appeared very easily. But when it was negative, they hardly appeared. If something was made to approach near to the lamp wall, it was found, that the discharge form was changed considerably, and, that the discharge was very sensitive to external influence.

(4) The Influence of Various Factors on the Discharges.

The Resonance Circuit.

As it was desirable to obtain an electric source of possibly sinusoidal wave forms, and, moreover, of possibly high voltage, a resonance circuit was used as an output circuit. The characteristics of the resonance circuit modified by the discharges might affect, it is feared, the discharges themselves. There should also be taken into account the reaction of this resonance circuit upon the oscillator circuit, even though couping was very loose. There was measured the resultant effective currents (including charging current as well), of both the lamp itself and the resonance circuit, and it was found that they were in the order of 7 m.a.s. or less for the discharges of types A and B, and about 35 m.a.s. for type C, while the corresponding currents in the resonance circuit were about 235 m.a.s. and 365 m.a.s. respectively. There was, then, investigated the influence of the degree of the coupling on the discharges, and, it was found that its influence, in the range used in this experiment, on $E_{A1}$, $E_{A2}$ and $E_{B1}$, $E_{B2}$ was quite small, but that was considerable on $E_{C1}$, $E_{C2}$.

As the lamp under test was put on the terminals of the variable condenser in the output circuit, there must be investigated the effect of the capacity on the discharges, because, for the same terminal voltage, the stored energy in the condenser is proportional to the capacity, and, thus, the quantity of the energy, it is feared, might affect them. At a certain fixed frequency, the relative magnitude of the inductance and capacity of the output circuit was varied, and the corresponding $E_{A1}$, $E_{A2}$, etc., were measured, and it was found that its effect, in the range used in this experiment, upon $E_{A1}$, $E_{A2}$ and $E_{B1}$, $E_{B2}$ was very little, but it was considerable upon $E_{C1}$ and $E_{C2}$.

The Effects of Screening and Series Resistance.

Covering the lamp wall with tin foil and keeping it at $\pm$ 200 volts against the earth or against either of the terminals, putting a battery between them, there was obtained the following result. It had practically no effects on the statical sparking and extinction voltages. But when the lamp was discharged by a.c.s, it affected $E_{A1}$, $E_{A2}$ and $E_{B1}$, $E_{B2}$ considerably. But this effect was due to putting the tin foil to the lamp terminal, it being almost independent of whether it was kept at the same voltage of the terminal, or whether it was kept at $\pm$ 200 volts against it. When the tin foil was connected to the spiral terminal, $E_{A1}$, $E_{A2}$, $E_{B1}$ and $E_{B2}$ were several volts smaller than when it was not connected.

As the effect of series resistance was considerable in the formation of the special discharge form, it was investigated whether it also had an affect on $E_{A1}$, $E_{A2}$, $E_{B1}$, $E_{B2}$, $E_{C1}$, and it was found that the resistance up to 2 megohms had very little effect upon them.

## Part III. Theoretical Considerations on the Experimental Results.

The Meaning of $E_1$ and $E_2$.

The $E_1$, which is called a minimum striking voltage in this paper, is the crest value of the minimum voltage which can start and maintain a discharge, from the neutral state, in spite of its successive striking and extinguishing, corresponding to each instant of any one cycle of the a.c. The $E_2$ is the crest value of the minimum voltage which can maintain a discharge after it has been once initiated, in spite of its successive striking and extinguishing corresponding to the respective instant of the following cycle of the a.c.

The gas discharge phenomena excited by high frequency currents will vary owing to the various relations between the gas pressures, the electrode distance and the frequency. If the mean free path be compared with the electrode distance, or if the maximum distance which an electron can travel in a half cycle be compared with the mean free path or the electrode distance, the influence of the frequency must be conspicuous. When the frequency is very high, electrons will be powerful agents for the ionisation by collisions, while positive ions, owing to their large masses, can hardly take part in it. Therefore, the electron motion in a free space, under the influence of an a.c. field, is considered, here. It is assumed that the electric field is in one direction, say $x$ direction, and will be $E+E_0 \sin wt$, where $E$ is a constant field and $E_0 \sin wt$ is a sinusoidal a.c. field, $E_0$ being its amplitude. The equation of an electron motion under this field, if it is assumed to be a charged particle, its mass and charge being $m$ and $e$ respectively, is as follows:

$$m\frac{d^2x}{dt^2}=e\,(E+E_0\sin\omega t) \tag{1}$$

By integrating the above equation,

$$v=\frac{dx}{dt}=\frac{e}{m}\left(Et-\frac{E_0}{\omega}\cos\omega t\right)+B, \tag{2}$$

$$x=\frac{e}{m}\left(\frac{1}{2}Et^2-\frac{E}{\omega^2}\sin\omega t\right)+Bt+C, \tag{3}$$

where B and C are the integration constants. The equations (2) and (3) express the velocity and displacement of an electron, respectively. The electrons are supposed to be in various states of motion in the free space, and, in general, it is assumed as follows:[7] $v=o$ when $t=t_0$ and $x=o$ when $t=o$. Then the constants are determined.

$$B=\frac{e}{m}\left(\frac{E_0}{\omega}\cos\omega t_0-Et_0\right),$$

$$C=0$$

The equations (2) and (3), then, become,

$$v=\frac{dx}{dt}=\frac{e}{m}\frac{E_0}{\omega}\left\{\left(\cos\omega t_0-\frac{E}{E_0}\omega t_0\right)+\left(\frac{E}{E_0}\omega t-\cos\omega t\right)\right. \tag{4}$$

$$x=\frac{e}{m}\frac{E_0}{\omega^2}\left\{\left(\frac{1}{2}\frac{E}{E_0}\omega^2 t^2-\sin\omega t\right)+\left(\omega\cos\omega t-\frac{E}{E_0}\omega^2 t_0\right)t\right\} \tag{5}$$

First, the two extreme cases, when the electric field is a pure a.c., are considered. $E=o$ and $t_0=\frac{\pi}{2}\frac{1}{\omega}$. Under these conditions,[8] the equations (4) and (5) become,

$$v=-\frac{e}{m}\frac{E_0}{\omega}\cos\omega t \tag{6}$$

$$x=-\frac{e}{m}\frac{E_0}{\omega^2}\sin\omega t \tag{7}$$

In this case, an electron oscillates about a mean position. $E=o$ and $t_0=o$. Under these conditions[9] the equations (4) and (5) become,

$$v=\frac{e}{m}\frac{E_0}{\omega}(1-\cos\omega t) \tag{8}$$

$$x=\frac{e}{m}\frac{E_0}{\omega^2}(\omega t-\sin\omega t) \tag{9}$$

In this case, an electron moves across the space with alternate acceleration and retardation without any reversal in the direction of motion. The motion of electrons under a pure a.c. field will be as follows:—The electrons whose velocities happen to be zero at the time near to $\frac{\pi}{2}\frac{1}{\omega}$, displace $x_1$ in one direction in the first half cycle, and $x_2$ in the second half cycle, $x_1$ being very nearly equal to $x_2$. In one alternation it covers a distance $x_1+x_2$, but actually approaches to one electrode by a small distance $x_1-x_2$. When $x_1$ and $x_2$ are less than the electrode distance, the electrons will travel more than an electrode distance before they reach the electrode. The general motion of the electrons up to the time they have a collision is, thus, a movement through a distance $x_1$ in one direction followed by a movement $x_2$ in the reverse direction, this process being repeated indefinitely till an electrode is reached. For such electrons there will be relatively but little loss of charge. The activity of a very rapidly varying field to maintain a discharge at very low pressure is, that in moving between the electrodes a large number of electrons cover a distance many times greater than the distance between the electrodes, and, thus, the chance of collision is very much larger than if the electrons pass straight across. When the pressure is very low, but not extremely so, such an effect will be more conspicuous as the frequency increases.

Next the case, when electrons are excited by an a.c. superimposed on a d.c. is considered. If, it is assumed that, $t_0 = \frac{\pi}{2}\frac{1}{\omega}$, or $t_0 = o$, the equation (4) becomes,

$$v = \frac{e}{m}\frac{E_0}{\omega}\left(-\cos\omega t + \frac{E}{E_0}\omega t - \frac{E}{E_0}\frac{\pi}{2}\right), \tag{10}$$

or

$$v = \frac{e}{m}\frac{E_0}{\omega}\left(1 - \cos\omega t + \frac{E}{E_0}\omega t\right). \tag{11}$$

From these equations, (10) and (11), it is seen that, under such conditions, the velocity in one direction will be increased considerably, its rate of increase depending upon the rates of $\frac{E}{E_0}$. On superimposing a d.c., many electrons will lose the chance to travel a distance many times greater than the distance between the electrodes, and, thus, the chance of collision is very much smaller than if there is no d.c. superimposed.

In these experiments, as the gas pressure was not very low, the mean free path was very small compared with the electrode distance. Moreover, the frequency was pretty high, but not extremely so, and, therefore, the high frequency characteristics appeared considerably, but not very conspicuously. And as the pressure was kept constant, and, therefore, the mean free path being constant, the electrons would have more chance[(10)] to reach the ionisation velocity before they had made a collision, as the frequency increased.

In investigating the high frequency discharge characteristics, the effect of rest ionisation, the change of the systems,[(11)] produced by the discharge, which are perhaps more easily ionised than the normal molecules, must also be taken into consideration. These effects are supposed to be more conspicuous as the frequency increases, and, if any other effect does not appear, these effects would make $E_{A1}$, $E_{A2}$, $E_{B1}$, $E_{B2}$, $E_{C1}$ and $E_{C2}$ become smaller as the frequency increases. But, the time-lag effect[(12)] of discharge must also be taken into consideration, which effect will make them larger as the frequency increases. From the standpoint of these general considerations, the experimental results are now discussed.

## The Discharge of Type A.

This kind of discharge may be produced as follows.

Some free electrons, which happen to exist in the space between the electrodes, will make collisions, depending on the way of their moving under the effect of the applied field, and thus produce new electrons. These latter electrons will, like the former ones, produce new electrons, and so on. Thus, at last, there will be produced many electrons, quite enough to occur for this kind of discharge, there being no necessity to produce electrons at the cathode, thus the cathode fall disappears. The voltage to produce this type of discharge, therefore, can even be smaller than the normal cathode fall. It does not depend upon the electrodes, but on the filled gas, and, theoretically, this can be so low as to the ionisation voltage of the gas. When the gas pressure is pretty low and constant, the higher the frequency, then, at the lower voltage, the discharge will be produced and maintained. The time-lag effect becomes very small for this kind of discharge. The experimental results confirm this supposition. The difference of $E_{A1}-E_{A2}$, under a pure a.c. field, increases considerably as the frequency increases. This is, perhaps, due to some residual effects. Once the discharge has been initiated, the applied peak voltage may be reduced, and the discharge may be maintained as long as the power supplied is sufficient to make good the energy losses, such as leakage at electrodes, walls etc.[13] When a d.c. is superimposed, $E_{A1}$ and $E_{A2}$ become larger than when it is not superimposed. They become the larger, the more the superimposed d.c. is increased even with the same frequency for the a.c. This is perhaps due to the loss of charge, since more electrons will reach the electrode straight across when a d.c. is superimposed, thus, this effect surpasses the reverse tendency produced under the residual effect as well as under the time-lag effect. Examination was made to see how the light affected $E_{A1}$ and $E_{A2}$, and it was found that $E_{A1}$ was a few volts lower when the gap was lighted by a carbon arc lamp than when it was in the dark space, while $E_{A2}$ was practically unchanged. But, when the gap was placed in an undamped high frequency field, $E_{A1}$ and $E_{A2}$ changed considerably, even when no visible electrodeless discharge due to the exciting field appeared in the lamp. Under this condition, $E_{A1}$ was lower by about 10–20 volts, and $E_{A2}$ were lower by about 5–10 volts, than when it was not excited. This same tendency existed under various frequencies of the a.c.s. Under a still stronger high frequency exciting field, this effect was, naturally stronger.

## The Discharge of Type B.

The $E_{B2}$ became lower as the frequency was increased, but in the experimental range, its minimum value was about equal to the statical extinction voltage of the lamp. This is a "Townsend Discharge" at low pressures, under the influence of high frequency currents, and it is also affected by type A, since the latter appears generally before the former when the voltage is increased, and remains longer when the voltage is decreased.

## The Discharge of Type C.

This is a usual glow discharge, but, as types A and B occur generally before it, their effects must be considered. Also the peculiar natures of the neon lamp itself must be taken into consideration. This can be seen from the irregular results of the experiments for this type. Here is discussed only the case when the superimposed d.c. was 100 volts and the frequency of the a.c. was varied. In this case, types A and B were not practically observed, and, at a certain voltage type C appeared abruptly, and when the voltage was, then, decreased, the area of the cathode covered by the negative glow became smaller, and at a certain point, it disappeared abruptly. As may be seen from the experimental results, $E_{C1}$ and $E_{C2}$ increased considerably as the frequency was increased,[14] this being just the reverse tendency from types A and B. The $E_{C1}$ and $E_{C2}$ were always higher than the statical sparking voltage. The discharge of type C is very strong and its discharging current is very large compared with those for type A or B, and thus, it is supposed, the time-lag effect will take part conspicuously in this case. After the instantaneous voltage has reached the sparking voltage, a certain quantity of charge must have flowed into the space, before the discharge occurs. And when this preparation has been done, the instantaneous value of the terminal voltage must be greater or equal to the sparking voltage. This kind of time-lag will appear of itself. The results are that, the higher the frequency, the larger $E_{C1}$ and $E_{C2}$ are, and they show that this kind of time-lag effect surpasses the residual effect as well as the other high frequency effects, which will make $E_{C1}$ and $E_{C2}$ become smaller as the frequency increases. The time durations, during which the instantaneous values of the terminal voltage are above the statical sparking voltage, corresponding to various frequencies of the superimposed a.c., are calculated for $E_{C1}$ and $E_{C2}$.

The Results are as follows:—

| Frequency of the a.c. | Time duration for $E_{C1}$ | Time duration for $E_{C2}$ |
|---|---|---|
| $3.0\times10^4$ cycles per sec. | $9.5\times10^{-6}$ sec. | $5.52\times10^{-6}$ sec. |
| $6.82\times10^5$ ,, ,, | $4.5\times10^{-7}$ ,, | $3.7\times10^{-7}$ ,, |
| $5.08\times16^6$ ,, ,, | $6.4\times10^{-8}$ ,, | $5.8\times10^{-8}$ ,, |

The time duration is smaller when the frequency increases. This may be partly due to the residual effect as well as to the other high frequency effects, which have been already explained, and partly due to the fact that, as the frequency is increased, $E_{C1}$ and $E_{C2}$ become larger, and, though the time duration is small, more current can flow into the space during the same time.

## Part IV. Conclusions.

Using a neon glim lamp the following conclusions were obtained.

1. Three types of stable discharges can be observed in a successive sequence as the terminal voltage is increased as well as when it is decreased, under the influence of high frequency currents.

2. The appearance of the three types depends on the frequency and also on the superimposed d.c. When the frequency is high, all of the three types can be observed, but if it is low, only one or two of them. When the superimposed d.c. is small, all of the three types can be observed, but when it is large, only one or two of them.

3. The $E_{A1}$ and $E_{A2}$ decrease as the frequency increases. They can even be smaller than the statical extinction voltages. The difference of $E_{A1}-E_{A2}$ becomes larger as the frequency increases.

4. When an a.c. superimposed on a d.c. is used as an electric source, $E_{A1}$ and $E_{A2}$ become larger, for the same frequency of the a.c., and they become larger the more the superimposed d.c. is increased.

5. The $E_{B1}$ and $E_{B2}$ decrease as the frequency increases.

6. The $E_{C1}$ and $E_{C2}$ increase as the frequency of the a.c. increases, in the case under the influence of an a.c. superimposed on a d.c., and type B and type A can not practically be observed.

I have much pleasure in thanking my assistants, Mr. M. Kadowaki and M. Saito, for the help they have given me in this investigation and also in thanking Mr. T. Koyanagi, for his help in making the figures.

The End.

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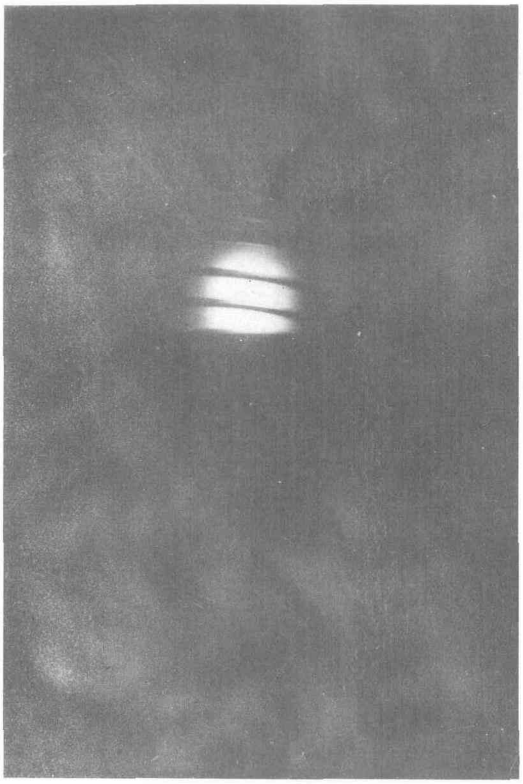
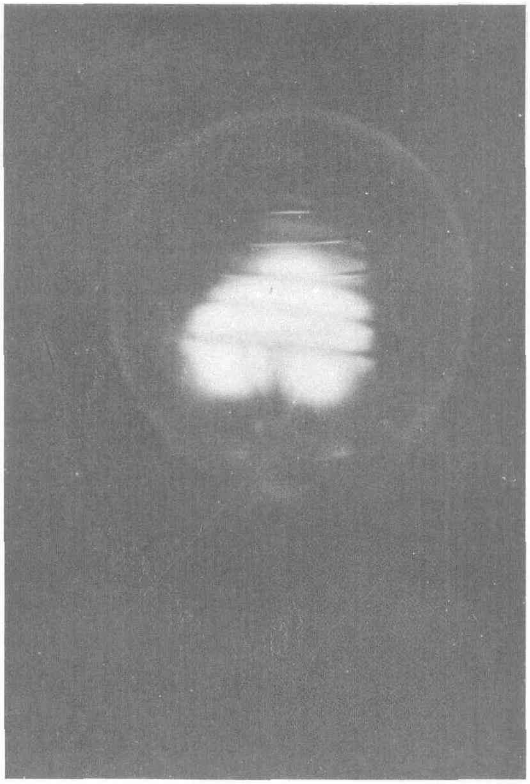
Fig. 4.

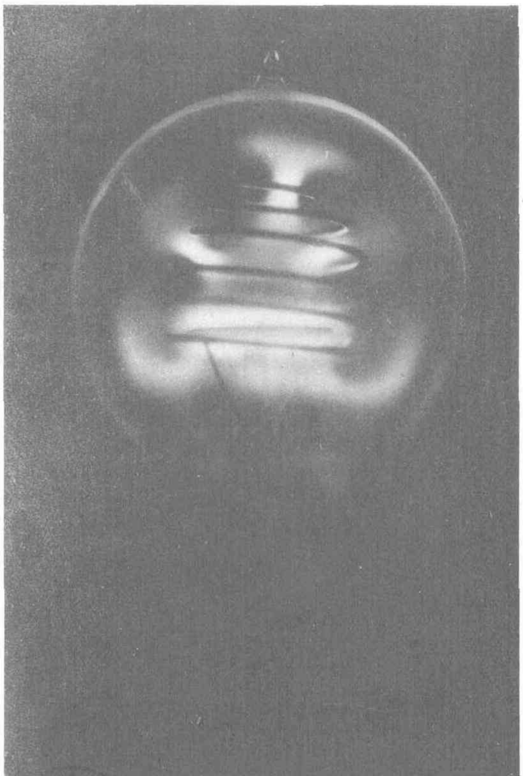
Type A



Types A and B



Dischange of Special Form



Type C