Physics. — *Anomalous variations of the sparking potential as a function of p_0d.* By F. M. PENNING. (Natuurkundig Laboratorium der N.V. Philips' Gloeilampenfabrieken, Eindhoven, Holland.) (Communicated by Prof. G. HOLST.)

(Communicated at the meeting of November 28, 1931.)

§ 1. *Introduction.*

According to PASCHEN's law the sparking potential V_s of a gas between parallel plates at a short distance is a function of p_0d (gas-pressure at 0° C × electrode distance). The general shape of the curves $V_s = f(p_0d)$ is shown in fig. 1; at high pressure the sparking potential is high because the electrons lose much energy before they reach their ionizing velocity, at low pressure the sparking potential is high because there are few ionizing collisions; at an intermediate value of p_0d, $(p_0d)_{min}$, V_s has a minimum value. Recently we have found deviations from the type of curve shown in fig. 1: in mixtures of neon with a small amount of argon we found two minima instead of a single one; for helium at values of $p_0d < (p_0d)_{min}$ the curve has the peculiar form shown in fig. 5.

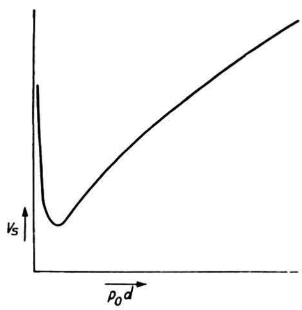

Fig. 1.

§ 2. *The double minimum in the curves for neon with a small amount of argon.*

These measurements were performed with two types of apparatus *A* and *B*. The tube *A* with two iron plates of 8 cm diameter at 2 cm distance is shown in fig. 2; it was intended in the first place for measurements with pure neon which will be described elsewhere [1]). The tube was filled with about 250 mm neon, the last small traces of impurities being removed by an arc discharge of 0.5 *A* with *Ca*-cathode in the side tube *D*. The desired neon-argon mixture was realised by opening one of the side tubes *F* which had been filled with argon beforehand. Then one of the side tubes *E* was sealed to the vacuum system over a liquid air trap, a manometer and a tap, the first being nearest to the tube. After shattering of the glassbulb in *E* the measurements could be taken.

[1]) Physica. To this article we refer also for further particulars as to the construction and operation of the tube.

Fig. 3 shows the results of two series of measurements, one for Ne[1]) one for $Ne + 0.0018\ \%\ Ar$. The curve for Ne has the normal shape, the other, however, shows two minima, which can be explained in the following way.

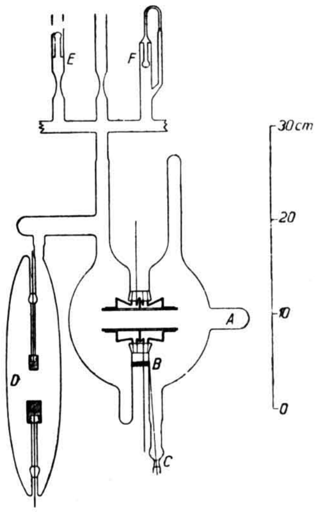

Fig. 2. (Tube A)

At large values of $p_0 d$ the sparking potential of neon is decreased very much by a small admixture of argon, because the metastable neon atoms ionize the argon atoms[2]). At low values of $p_0 d$ this effect will only have a small influence; the probability for the formation of metastable atoms is not large and those which are formed have a short life time, because of their returning into the normal state at the electrodes. Therefore in this region of $p_0 d$ the value of V_s for $Ne + 0.0018\ \%\ Ar$ is about the same as that for Ne and increases in about the same way with increasing values of $p_0 d$. At still larger values of $p_0 d$ the effect of the metastable atoms becomes appreciable and V_s decreases until a second minimum is reached. This interpretation is confirmed by other experiments with the second tube B having also iron electrodes of 8 cm diameter but at a distance of 12 cm, mounted in a glass tube of 10 cm diameter. Comparison of figs. 3 and 4 shows that even with pure neon the values of V_s for the same value of $p_0 d$ are not the same in both cases which is in apparent contradiction to the law of PASCHEN. However, this law holds only for distances of the

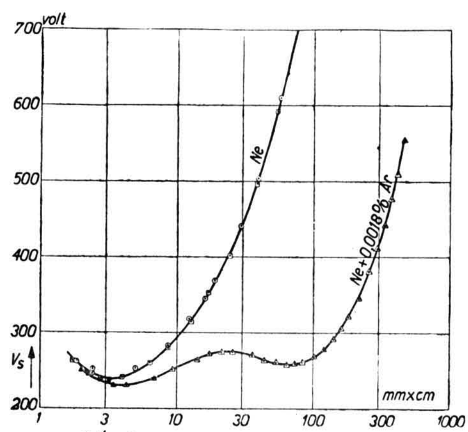

Fig. 3. (Tube A, $d = 2$ cm)

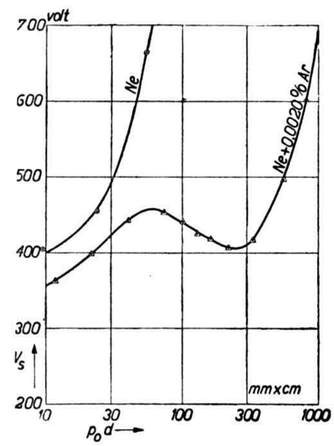

Fig. 4. (Tube B, $d = 10$ cm)

[1]) The neon contained about 1 % helium, but the influence of this admixture on the sparking potential is small.

[2]) See F. M. PENNING, Phil. Mag. **11**, 961, 1931; Zs. f. Phys. **57**, 723, 1929 and former publications.

electrodes which are small compared with their diameter, otherwise the side diffusion of electrons and ions is not negligeable. In the tube B this condition is certainly not fulfilled, therefore the sparking potential is higher. Now the side diffusion of the metastable atoms is still larger than that of the charged particles which are directed by the electric field, and consequently at the same value of p_0d the fraction of metastable atoms which is destroyed at the walls is much larger in tube B than in tube A. This explains why for $Ne + 0.002\ \%\ Ar$ the maximum in tube B occurs at a value of p_0d which is about three times as large as that in tube A. In addition the double minimum is still more pronounced in fig. 4 than in fig. 3.

§ 3. *The sparking potential of helium for values of* $p_0d < (p_0d)_{min}$.

The tube of fig. 2 is not suited for measurements in this region because here the sparking may occur between the back sides of the electrodes Therefore the measurements were made between the plane ends of two cylinders fitting exactly in a glass tube. Both cylinders could be moved, p_0d being varied in this case by changing d. Now for a gas pressure of 0.7 mm He the sparking potential curve for $p_0d < (p_0d)_{mi}$ has the peculair form shown in fig. 5; this curve has a minimum with respect to d [1]). In a certain range of electrode distances the sparking potential has three different values, two for increasing and one for decreasing potential difference. This effect is still more pronounced in another apparatus described in § 4 (figs. 7 and 8); the results of these measurements are plotted in fig. 6. For $2.2\ \text{cm} < d < 2.8\ \text{cm}$ the current suddenly dropped to zero after reaching a certain value, the potential at the same time rising to a high value inside the region BCD (fig. 5), the sparking potential on CD and on BC could then be determined by increasing resp. decreasing the potentiel difference of the potentiometer. For $d > 2.8$ the discharge did not stop when the current was increased; to measure in this region the electrode distance was at first adjusted to a small value where a high potential difference could be applied; then, with this potential difference remaining between the electrodes, the distance was increased up to the desired value.

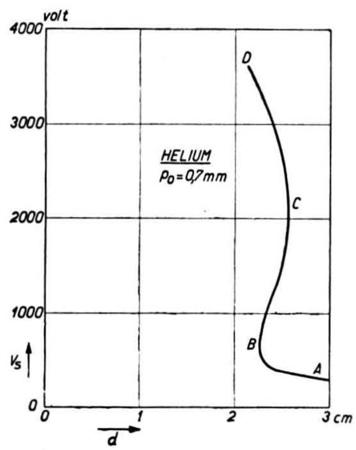

Fig. 5.

This form of the curve for the sparking potential may be explained in the following way.

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[1]) These measurements are described more fully in Physica (l. c.).

When an electron leaves the cathode it will ionize atoms on its way to the anode, the new electrons will in turn produce other ions and electrons and so on. If N is the total number of ions produced in this way by one electron leaving the cathode, then according to HOLST and OOSTERHUIS [1]) sparking will occur when $N\gamma = 1$, γ being the number of

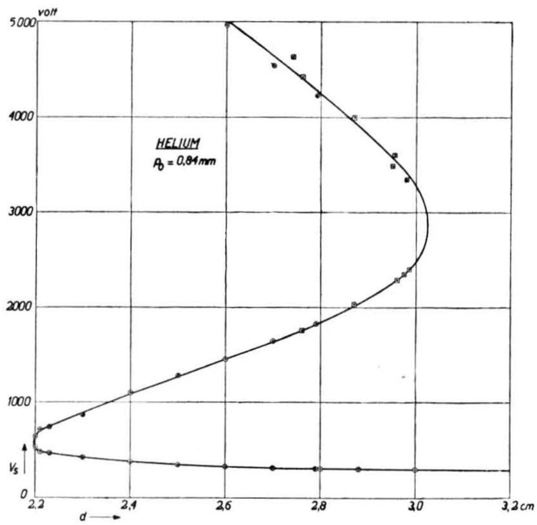

Fig. 6.

electrons liberated from the cathode per positive ion [1]). When, for $p_0 d < (p_0 d)_{min}$, d is decreased, the number of atoms between the electrodes decreases and also the number of ionizations N. So, in order to fulfil the condition $N\gamma = 1$, N should be increased which can be done by increasing the potential difference. However, the probability of ionization by an electron does not increase continually with increasing electron velocity, but passes through a maximum. According to COMPTON and VAN VOORHIS [2]) this maximum is reached for helium at an electron velocity of about 200 volts. When, however, the potential difference between the electrodes becomes so large that the number of ionizations N is at its maximum, a decrease of $p_0 d$ cannot be compensated by increasing the potential difference: for lower values of $p_0 d$ no sparking is possible, the sparking potential curve bends to the right (point B in fig. 5). For larger values of d two sparking potentials occur, because a certain value of N can be realised as well to the right as to the left of the maximum in the curve for the ionizing probability of the electrons.

In reality the circumstances are more complicated as was supposed in

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[1]) G. HOLST and E. OOSTERHUIS, Versl. Kon. Ak. v. Wet. Amsterdam **29**, 849, **1920**, **30**, 10, 1921; Phil. Mag. **46**, 1117, 1923.

Compare F. M. PENNING, Proc. Amsterdam, **31**, 14, 1928; **33**, 841, 1930.

[2]) K. T. COMPTON and C. C. VAN VOORHIS, Phys. Rev. **27**, 724, 1926.

the simplified discussion given above: first γ is not a constant but increases with increasing ion velocity, secondly at sufficiently high velocity the ionization of atoms by collisions with positive ions is no longer to be neglected. These effects cause again sparking when the potential difference is sufficiently increased (part CD of the curve). The question as to whether the curve for V_s should show a minimum with respect to p_0d or not, depends on the way in which the electron building power of the positive ions increases as the ionization by the electrons diminishes. Experimentally too little is known about these elementary processes to make any predictions. With the first described tube this minimum was up to the present found only in helium although several other gases were examined.

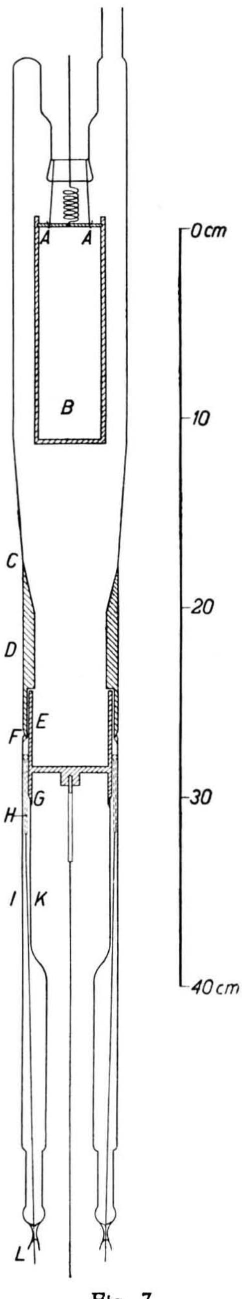

Fig. 7.

§ 4. *The current-voltage characteristics for low values of p_0d in helium.*

As mentioned in § 3 the first measurements of the sparking potential were made between the plane ends of two iron cylinders fitting exactly in a glass tube, and it was found that sometimes the discharge extinguished when the voltage on tube + resistance

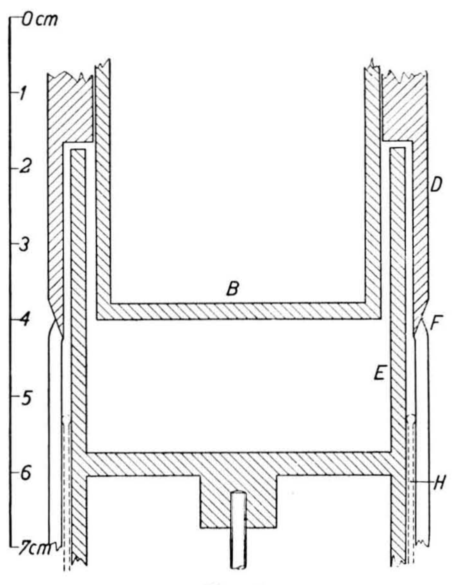

Fig. 8.

was increased. However, this phenomenon could not be reproduced very well, probably because of charges on the glass wall. Therefore another apparatus was designed where the wall of the discharge space was of metal kept at the same potential as the anode.

This tube is shown in fig. 7 (details in fig. 8). The cathode is a hollow iron cylinder *B*; during the evacuation of the tube it was suspended on two hooks *AA*, as shown in fig. 7, in order to allow a thorough outgassing by means of high frequency currents. During the measurements *B* rests in the hollow chrome iron cylinder *D* (fig. 8), the internal diameter of *D* being only 0.2 mm larger than the external diameter of *B*. The space between *D* and *E* and also between the outer wall of *B* and the inner wall of *E* is only 1 mm. The chromium iron cylinders are sealed unto the glass at *C*, *F* and *G*. The sparking potential is measured between the lower plane end of *B* and the bottom of *E* (distance *d*). Spurious sparking is only possible between the lower end of *D* and the outer wall of *E*. This sparking was prevented by a gauze *H* making contact with *E*, the distance between the ends of *D* and *H* being smaller than *d*. The electrostatic attraction between *D* and *H* was so large that it was necessary to keep *H* in place by wires sealed into the glass at *L*.

With this arrangement of the electrodes the electric field between the plates is not homogeneous, so the conditions are still more removed from

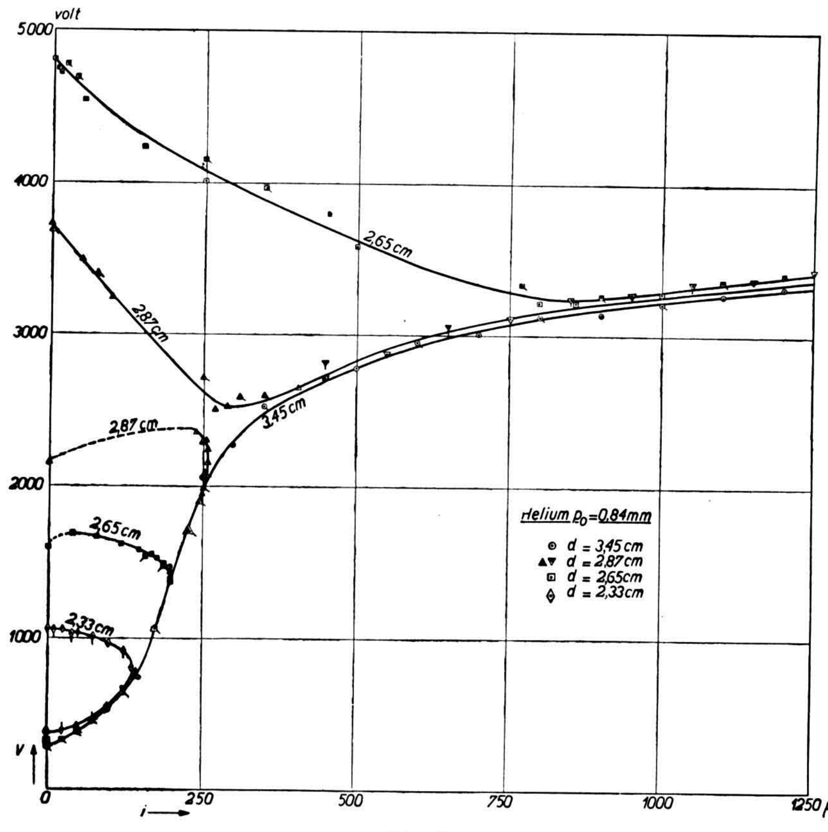

Fig. 9.

the ideal case of large plates at a small distance than in the tube used before. Nevertheless for $p_0d < (p_0d)_{min}$ the sparking potential will depend chiefly on d.

For the measurements the tube was placed at a certain slope, B being displaced by tapping at the wall of the tube. With this arrangement of the electrodes the characteristics proved to be much better reproducible than with the apparatus used before. Some series of measurements are shown in fig. 9; they were taken in both directions, the points with increasing potentiometer potentials being marked by undashed, those with decreasing potentials by dashed marks. For $d > 2.9$ cm ($p_0 = 0.84$ mm and constant) the characteristic shows the normal shape, for smaller values of d it consists of two different branches, the distance between them becoming larger and larger as d decreases; finally for $d = 2.2$ cm the lower branch disappears.

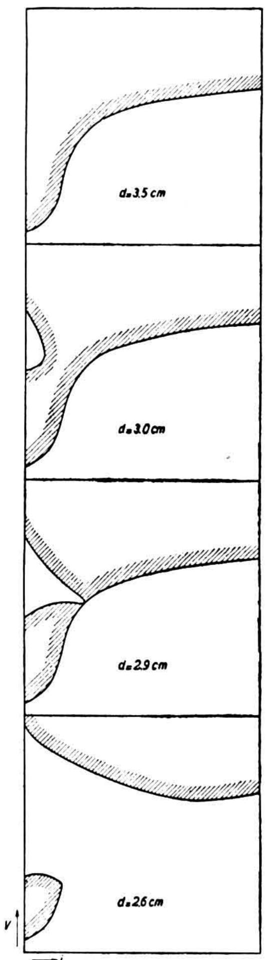

Fig. 10.

The explanation is the same as for the phenomena of § 3, indeed the curve of fig. 6 may be obtained by taking from fig. 9 the values of V for $i = 0$. For larger currents the electric field is modified by space charges, therefore the ionization by the electrons is also changed and thus, for constant d, the potential difference necessary to maintain a certain stable current depends upon the current.

This behaviour of the characteristics entails remarkable consequences with regard to the stability condition of the discharge. The current voltage characteristic for a certain distance may be considered as a boundary between two current voltage regions [1]). In one of them at a constant value of the potential, the current *increases* with time:

$$\left(\frac{\partial i}{\partial t}\right)_{V\,const.} > 0 \text{ (positive region, dashed in fig. 10),}$$

in the other it *decreases*:

$$\left(\frac{\partial i}{\partial t}\right)_{V\,const.} < 0 \text{ (negative region).}$$

The question as to which is the positive and which the negative side of the characteristic may be answered by considering the case for $i = 0$ (sparking potential). It should be remarked that one point in the current potential diagram may correspond with several different (transient) discharges because of the space charge being distributed in different ways.

[1]) Comp. G. VALLE, Sitzungsber. Ak. Wien **127**, 1339, 1918; Phys. Zs. **27**, 473, 1926.

Therefore we can apply the above considerations only for the points near the characteristic where the space charge distribution is still about the same as at the neighbouring points of the characteristic itself.

Fig. 10 shows schematically how the positive and the negative regions change with decreasing d. The case for $d = 3.5$ cm is the normal one with the positive range above, the negative range below the characteristic. At $d = 3.0$ cm the characteristic, measured in the usual way by increasing the potentiometer potential or decreasing the resistance, has about the same form as that for 3.5 cm, but in addition for small currents a small negative region develops, as follows from the data of fig. 6. For d about 2.9 cm the two negative regions touch and for smaller distances two separate positive regions exist. Finally the region to the left disappears completely.

With a resistance R and a potential difference U on tube + resistance, the possible discharges are found at the intersection of the characteristic and the "resistance line", cutting the V-axis at $V = U$ and making an angle $= arc\ tg\ R$ with the i-axis. Now according to KAUFMANN [1]) a stable discharge is only possible when $R > -dV/di$ (P in fig. 11 with the resistance R_1). For an intersection point where $R < -dV/di$ (P with the resistance R_2) the discharge is unstable, the current increasing continually until a second intersection point where $R > -dV/di$ is reached (T). At the time this rule was given, only the ordinary form of the characteristic was known with the positive range above it. However, we have seen that the positive region can also lie below the characteristic, e.g. at the point Q in fig. 11. In this case obviously the necessary condition for stability is reversed: $R < -dV/di$ (Q unstable for R_1 and stable for R_2).

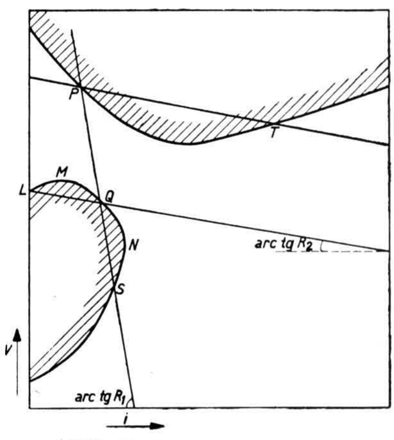

Fig. 11.

With regard to these two possibilities we may now formulate the condition as follows: the intersection point of characteristic and resistance line corresponds only to a stable discharge, when at this point the resistance line followed in the direction of increasing i, passes from the positive into the negative region [2]). Consequently the part MN of the characteristic (fig. 11) can be measured only with a small value of R, the part LM cannot be measured at all. Therefore in fig. 9 parts of the characteristics

[1]) W. KAUFMANN, Ann. d. Phys. **2**, 158, 1900.

[2]) This rule gives only the *necessary*, not the *sufficient* condition for stability; even when this condition is fulfilled oscillations may occur ("relaxation oscillations"), see e. g. F. M. PENNING, Phys. Zs. **27**, 187, 1926. However, for the present we do not consider this point in more detail.

corresponding to *LM* are represented by dotted lines, the point *L* itself may be deduced from fig. 6, at least when the lag in the sparking is negligeable.

Finally fig. 12 shows for the case of two positive regions the successive

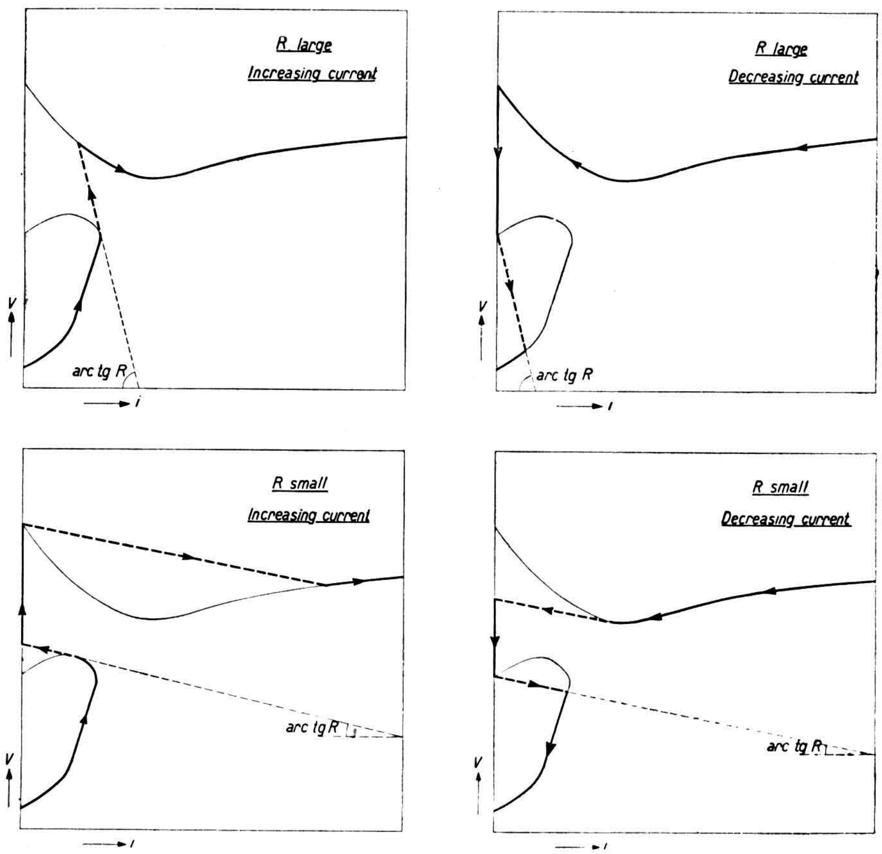

Fig. 12.

values of currents and potentials when the potentiometer potential is increased or decreased, 1⁰. for a large value, 2⁰. for a small value of *R*. This behaviour is in accordance with the above considerations.

My thanks are due to Mr. J. MOUBIS and Mr. C. C. J. ADDINK for their assistance.

Eindhoven, 24th November 1931.