ELECTRICAL DISCHARGES IN HIGH VACUUM*

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Measurements have been made to investigate the mechanism of the breakdown in high vacuum and of the discharge preceding the breakdown. The results of the measurements have been at variance with the theory of VAN DE GRAAFF and TRUMP as well as with that of CRANBERG and have clearly shown that the mechanism of a breakdown in high vacuum is identical with the events observed by BOYLE and al. at very low voltages. Thus it was found possible to form a uniform picture by which many already wellknown phenomena can be explained.

1. Introduction

When reducing the gas pressure in a discharge tube it is observed that at very low pressures, where the free path of the electrons is greater than the electrode distance, the character of the discharge changes fundamentally. This type of electric discharge is generally known as vacuum discharge. The character of the discharge is actually independent of the quality and pressure of the gas at an electrode distance of a few mm, resp. cm for pressures of less than 10^{-4} mm Hg ; dependence on these being observed only when surface qualities of the electrodes are effected. This gas discharge "without gas" makes it possible to examine the electrode events of a normal gas discharge on the one hand, and is of great practical importance when designing accelerating electrodes of electrostatic accelerators and when operating X-ray-blitz devices, on the other hand.

A vacuum discharge may occur at low voltage (a few kV) as well as at high voltage ; the phenomena in the two groups being explained by different mechanisms. The problems in connection with discharges at high voltage are the most controversial and unclarified. The present paper contains a critical analysis of theories dealing with the latter effect. An attempt at interpretion of the phenomena leads to the conclusion that there is no essential difference between the breakdown at low or at high voltages.

2. The theory of the electron-ion exchange

The most natural explanation as to the mechanism of the phenomenon would be to attribute the vacuum breakdown to the cold emission electrons

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produced by the strong field occurring at the cathode. Measurements have been made by VAN DE GRAAFF and TRUMP concerning the breakdown occurring between a stainless steel ball and a plane electrode at voltages up to 700 kV [1]. They found that the field strength at the cathode producing a breakdown was more than 3 MV/cm at 0,1 mm distance of the electrodes, where as it was lower than 100 kV/cm at 70 mm distance. Thus it was assumed that the critical condition for breakdown depends not only on the field strength but also on the absolute value of the voltage. According to the assumption of these authors each electron emitted by the cathode produces a positive ion when impinging on the anode, these ions releasing in their from secondary electrons by their impact on the cathode. The critical state sets in when the number A of ions produced by one electron and the number B of electrons released by one ion fulfill the condition $A \cdot B \geqq 1$. In such cases chain multiplication of the process initiates a breakdown.

VAN DE GRAAFF and his collaborators as well as other authors have made many measurements to determine A and B [1], [2], [3], [4] and [5]. The results of all these measurements contradict the above theory namely AB always proved to be much smaller than 1. All the same this theory has not yet been abandoned.

In order to check the correctness of the above assumption we have made measurements to determine the ratio of electrons and positive ions produced in a vacuum discharge. For this purpose we have perforated one of the two plane electrodes providing it with a grid; the particles passing through the grid were then captured by an insulated dial target (Fig. 1). Alternating

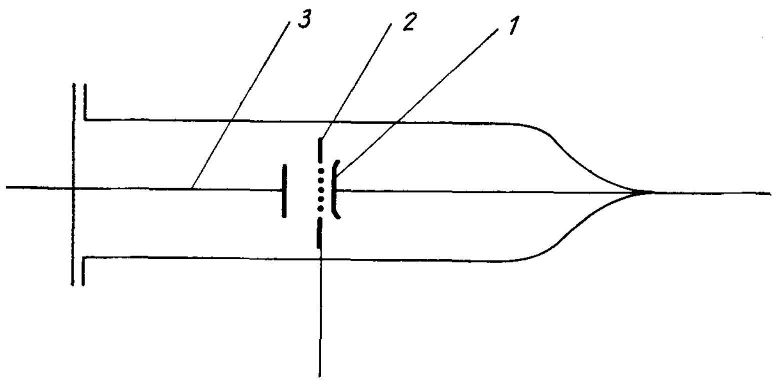
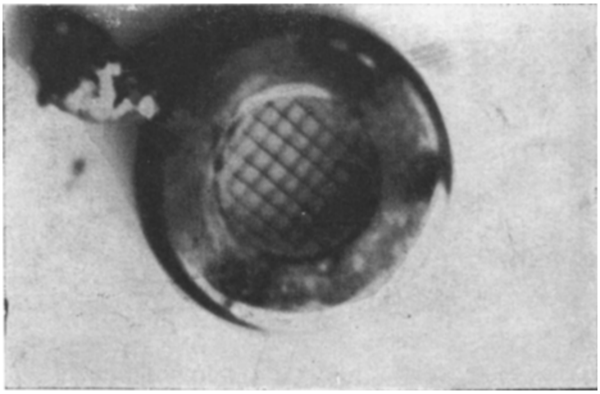


Fig. 1a. Apparatus for measuring electron/ion ratio. 1. High-voltage electrode, 2. Grounded grid electrode, 3. Target electrode

the polarity of the electrodes alternately positive ions and electrons were captured by the target. The distance between the electrodes was about 1 mm, the voltage 20—30 kV. In order to prevent a breakdown from destroying the electrodes, we inserted a protective resistance of 100 MΩ in the circuit. The voltage was adjusted to obtain equal current at both polarities (e. g. 100 μA). As a result of the measurement the proportion of negative to positive particles was found to be 1000 : 1.[1]



1b. Photograph of the grid electrode

The result of this measurement is in accordance with the published measurements of the coefficients A and B [1], [2] and [3] and disagrees with the theory of exchange. Theoretically the low values (10^{-4}—10^{-3}) of the coefficient A are quite acceptable too since it is difficult to explain an energy transfer by an electron impinging on a metal ion about 10^5 times its mass which would force the ion to depart from the metal.

3. The clump theory

Cranberg's theory gives an entirely different explanation of the phenomenon of vacuum breakdown. According to his assumption owing to the strong field at the electrode surface macroscopic pieces are torn from the electrodes and these colliding with the other electrode produce there a high local rise in temperature. This would explain the critical condition of the breakdown being dependent both on the voltage and the field strength. To prove his statement Cranberg has shown that the measurements of [1] and also other measurements can be interpreted by this theory. His assumption seems to be supported by measurements, where a material migration has been found before [7] and during [8] the breakdown.

[1] In the meantime a paper was published by Bourne [9]. He measured the electron-ion ratio in a different way and obtained in respect of steel electrodes results in agreement with the above.

The main difficulty of this theory lies in the fact that very small electrostatic forces are at play, hardly capable of overcoming the cohesion forces of the material. For instance in measurement [1] a breakdown occurs at 100 kV/cm with a corresponding power density $F = {}^1/_2\varepsilon_0\, E^2 = 4{,}4$ g/cm², but even supposing that at some part protruding due to the surface unevenness of the electrode the field strength increases 100 times we do not get more than $F = 44$ kg/cm². This value is very small compared with the strength

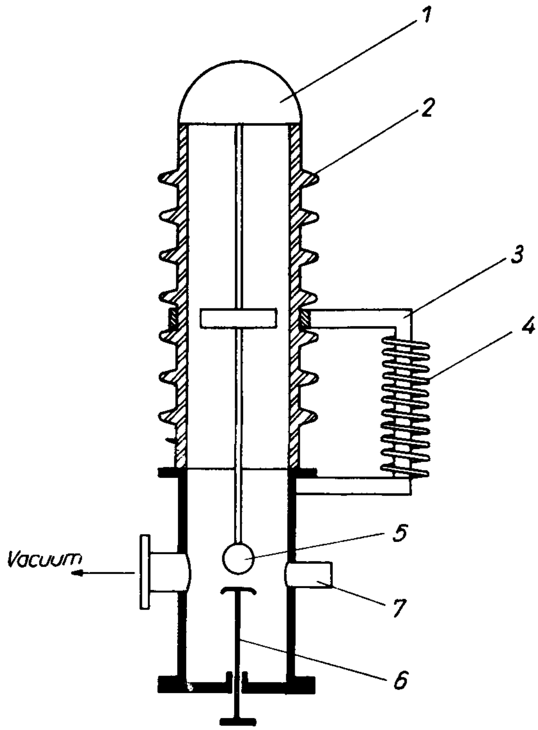


Fig. 2. 1. High-voltage terminal, 2. Porcellan insulator, 3. Iron yoke, 4. Magnetic coil, 5. High-voltage electrode, 6. Adjustable grounded electrode, 7. Vacuummeter

limit of the electrode materials ($\sim$ 1000 kg/cm²). Since, however, the theory gives a satisfactory explanation for the results reported in [1] we considered it worth while to carry out a control experiment.

The principle of measurement is the following. Using steel electrodes a magnetic field from a coil parallel to the electric field causes an effect opposite to the latter. The magnetic field makes the iron pieces stick to the electrode. If Cranberg's assumption is correct, breakdown must not occur, when applying an adequate magnetic field ; or at least it should occur only at higher voltages. We calculated both the forces acting on a ball placed in an electric and a magnetic field, respectively and in respect of the latter verified our results experimentally. The magnetic field applied was about 350 Gauss, which compensates a tearing force produced by an electric field of about 10^5 V/cm. There was, however, no difference in the results from the measurements effected with and without magnetic field, nor in the currents preceding the breakdown or in the values of the breakdown voltage. The electrodes were similar to those used by VAN DE GRAAFF and TRUMP with the difference that the non-magnetizable stainless-steel electrodes had to be exchanged for normal steel electrodes. The measuring arrangement is shown in Fig. 2.

With the same arrangement we made the following measurement: the dark discharge prior to the breakdown is followed by an X-ray radiation.

Fig. 3. Counts versus current curve

For a fixed voltage the flow of current varies with the electrode distance. The potential being constant the efficiency of producing bremsstrahlung, the geometry, etc have no effect, thus when measuring with a G. M.-counter the intensity of the X-ray radiation will be proportional to the number of electrons involved in the discharge. Results of such measurements are shown in Fig. 3. It can be seen, that the number of electrons is proportional to the current. These measurements while rendering the clump theory improbable at the same time also support our result, according to which the electrons are present in the discharge in an overwhelming majority as compared to the positive ions. According to some authors [10] the negative ions also play an important part in the discharge. This assumption too is contradicted by our measurements. Namely, it is hardly acceptable that the probability of electron emission and clump-tearing and ion emission, respectively should all depend in the same manner on the electric field (causing the change of the current).

All our measurement prove, in accordance with our assumption, that only the electrons play an important part in the phase of the discharge prior to the breakdown.

4. Investigation of the pre-breakdown

Experience gained in investigations concerning the breakdown of accelerating electrodes in static accelerators shows that the breakdown is mostly preceded by the deterioration of the vacuum. This suggests that the pre-breakdown discharge involves to a high degree the release of gases and vapours and that the effective breakdown takes place in this gaseous space. Thus the breakdown can be divided into two independent sections.

1. Pre-breakdown discharge which consists in the release of the electrons from the cathode.

2. The pre-breakdown discharge releases vapour and gas from one (or both) of the electrodes, the pressure between the electrodes increases and thus the actual breakdown becomes a common gas discharge.

In order to study the mechanism of the pre-breakdown discharge we first examined whether the critical field strength decreases when greatly increasing the electrode distance. Critical field means here the gradient at the cathode at which a given current flows. The measurement was made with the equipment shown in Fig. 2 with electrodes similar to those in the above experiment. In the course of several measurements it has been proved that reproducable results could only be obtained at low intensities when the measurement was of short duration. Typical curves are shown in Fig. 4. It can be seen that the field intensity required to produce a given current shows first a tendency to decrease and later becomes nearly constant. This is in complete agreement with the work of Boyle, Kisliuk and Germer [11] whose paper has been published while our measurements were going on and who made similar measurements in connection with the problem of electric contacts at much lower voltages ($<$ 2000 V). As is also indicated by these authors such a small value and decrease of the field strength does not contradict the assumption that the current is of cold-emission origin. Owing to the unevenness of the cathode surface the maximum field strength produced at the emitting peaks is β-times the macroscopic cathode gradient E, β increasing first rapid then more slowly with growing electrode distance.

To prove, however, directly that the pre-breakdown discharge has in fact the character of a cold emission, we have to show that the relation between the field strength and current intensity follows the Fowler-Nordheim law. For this purpose we plotted the current-voltage function at a given electrode distance, taking care that the recording of each point should take a short time only as otherwise the results could not have been reproduced. In case of cold emission the curves ln $I - f(1/E)$ have to be almost linear [12], [13], [14] and [15] (Fig. 5). As we may notice this condition is fulfilled, the difference being that in case of high current intensities the curves deviate downwards from the linear. We shall return to the cause of this later on. Quite similar curves have been obtained by BOYLE and al. [11] at otherwise absolutely

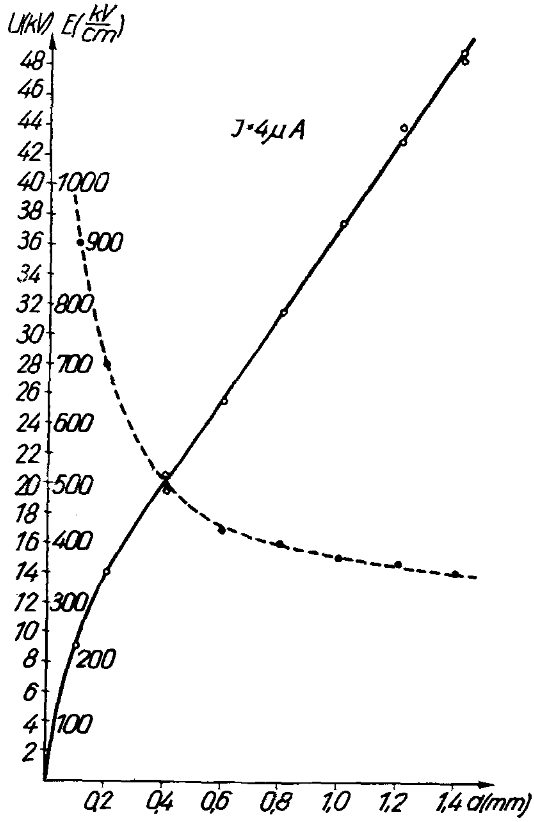


Fig. 4. Voltage (— — —) and cathode gradient (- - - - -) at constant current as a function of electrode separation

different conditions. The curves can be evaluated as usual. Assuming for work function $V_a = 4$ eV, at $d = 0{,}1$ mm we obtain $\beta = 60$ and at $d = 1{,}0$ mm. $\beta = 190$ from the slopes of the straight lines. These values of β are too great in comparison with those obtained by SCHOTTKY who estimates them to be of the order of 10 [16]. His calculations however, are very rough and we have to take into consideration that among the million or so micropeaks that having the highest β will emit ; certainly statistically even very pointed peaks must occur. There might also be places where V_a is considerably smaller than 4 eV due to the impurities. The values reported here, however, are within reasonable limits.

On the basis of the curves we have an other further possibility for checking the estimate for the β-s. The ratio of the β-s belonging to two different curves can also be obtained by plotting the ratio of the E-s corresponding to the points of the curves at $I =$ const. (Here it was assumed that the area of emitting surfaces was identical for both curves.) This control also fully supported our statements.

From the intersection points of the straight lines with the $1/E$ axis we

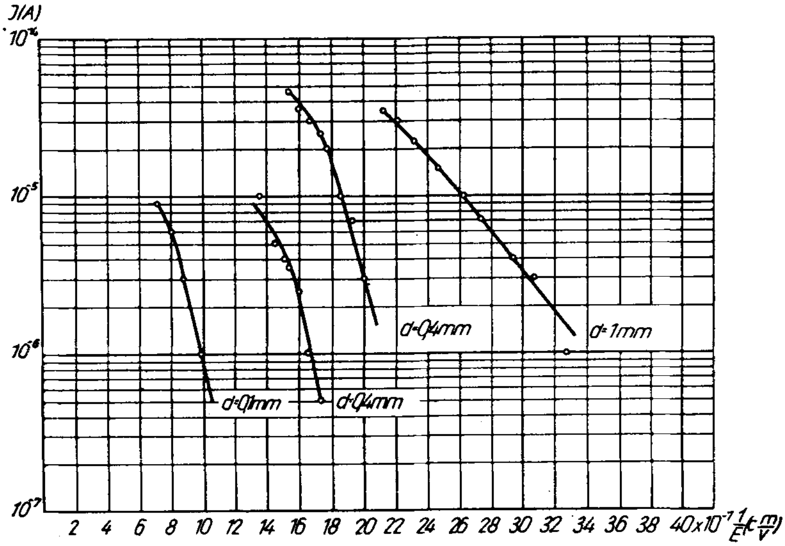


Fig. 5. LnI versus *1/E* curves with different electrode separation as parameter

may drow conclusions as to the area of the emitting surface. The order of magnitude of the surfaces thus calculated is $\sim 10^{-12}$ cm^2. This result indicates that the emission takes place from very pointed peaks and thus the big values for β are justified.

The systematic deviation of the curves from the straight line is easy to explain on the basis of the above results. 10^{-5} A means a current density of 10^7 A/cm^2 on a surface of 10^{-12} cm^2, where the emission is already limited by the space charge. This has already been observed on single well-defined peaks [14], [15].

Using the above results many phenomena which have up to now remained unexplanied may now be accounted for. It is obvious for instance why in order to obtain reproducible results it is necessary to restrict oneself to small currents and short times of observation. As a matter of fact high current density is sufficient to melt the micropeak in consequence of which its surface and form change. The emission in this case may be transferred to another peak, or it may continue on the same peak, but with a different value of β. The result of a measurement of longer duration (about half a minute per point)

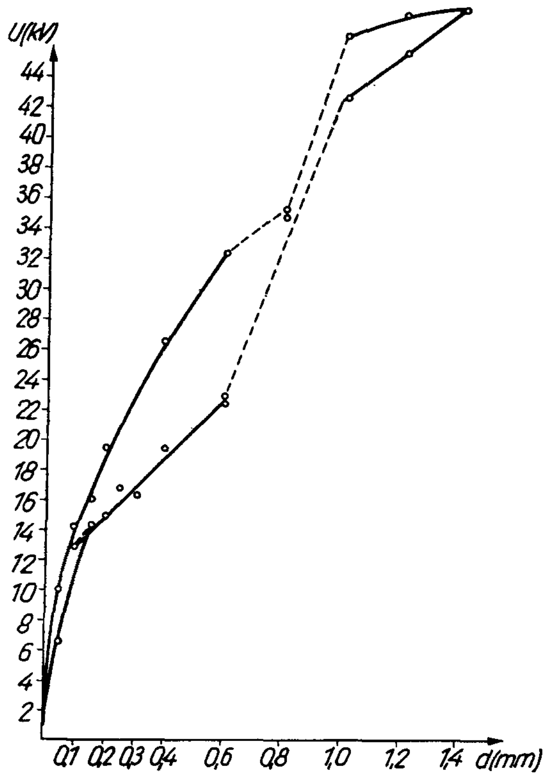


Fig. 6. Voltage versus electrode separation at constant current, obtained by prolonged measuring of every point. The arrows show the order of obtaining the individual points. The solid lines belong probably to different emitting peaks

is plotted in Fig. 6 which shows how the characteristic of the emission changes. The peaks flatten in general after the melting, the same current requires a higher voltage, the cathode "gets better". This is one physical reason for the long-used conditioning of electrodes of accelerating tubes.

5. The mechanism of the breakdown

On the basis of the mechanism of the pre-breakdown described above the process of the breakdown can be outlined as follows. The electrons produced by a small emitting peak hit the anode causing there a great local rise in temperature. Calculating for instance with a current of 100 μA and a voltage of 100 kV one obtains an output of 10 *W* which affects a very small area of the anode surface. This is quite sufficient to produce local outbreaks of gases and vapours. In the gaseous space thus produced the electrons are ionizing and the produced positive ions on the one hand increase the field intensity at the cathode by forming a space charge [11] while on the other hand they increase the electronic flux by inducing secondary electrons. The process multiplies automatically and soon generates so much gas that a regular gas discharge occurs. Thus we have a picture as to how the material of the anode migrates to the cathode and this explains why a smaller cathode gradient is needed to initiate a breakdown at higher voltage. In such cases small emission currents produce greater output on the anode, thus a release of gas starts al-

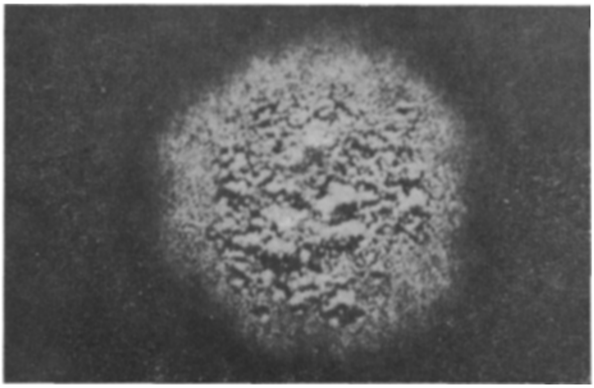


Fig. 7. Surface of an electrode after several vacuum breakdowns

ready at lower fields. Fig. 7 shows highgrade melting and destruction of the electrodes after a few breakdowns the electrodes originally showing a finely polished electrode surface.

It is interesting, however, that Van de Graaff and Trump have reported breakdown at very high voltages even at a very small cathode gradient. But a thorough examination of their curves shows that they did not plot the field strength occurring at the cathode but the mean field produced by the relation U/d. In case of a sphere and a plane electrode the maximum field strength on the surface of the sphere is higher at great distances than the one plotted. The corrected curve together with the original one is shown in Fig. 8. It is of interest to notice that the curves show an ascending tendency for greater distances. This can have several causes. First more gas is needed at a greater electrode distance, on the other hand the conditons of gas conductance, its pumping off by the pump are much better. Another cause may be higher scattering of the electrons emerging from the cathode at a greater electrode distance, thus impinging on a larger anode surface. For heating a larger anode surface, however, a higher output is needed i.e. at greater electrode distances it is important to impart higher energy to the electrons. Evaluation of this problem requires further work.

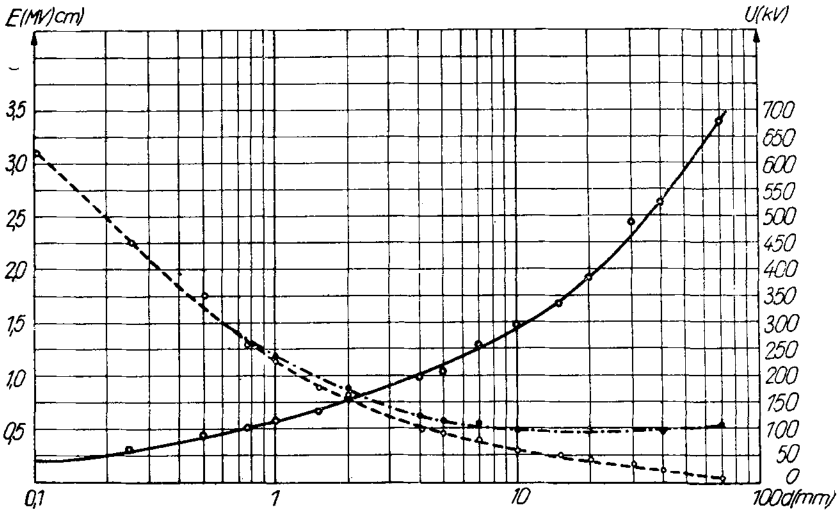


Fig. 8. The plot of TRUMP-VAN DE GRAAFF and the corrected critical cathode field strength curve. (— — —) voltage, (- - - -) field strength, (-.-.-.-.-) corrected field strength

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ЭЛЕКТРИЧЕСКИЕ РАЗРЯДЫ В ВЫСОКОМ ВАКУУМЕ

Г. ШМИТ

Резюме

Производились измерения для исследования электрических разрядов в высоком вакууме. Результаты измерения противоречат теории Ван дэ Графа, Трумпа и Кранберга, и явно показывают, что механизм разряжения в высоком вакууме идентичен с явлениями, обнаруженными Бойлом и др. при малом напряжении. Это позволило развить единую теорию, которая может объяснить и другие, хорошо известные явления.