Effect of anode material on the breakdown in low-pressure helium gas

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Abstract. An experimental study of the electric breakdown in helium gas for the plane–parallel electrode configuration has been conducted using a copper cathode and a variety of anode materials: copper, aluminum, stainless steel, graphite, platinum-plated aluminum and gold-plated aluminum. According to the Paschen law for studied electrode configuration, the breakdown voltage is a function of the product of gas pressure, $p$, and inter-electrode gap, $d$, that is $V_B = f(pd)$ [8]. The Paschen curve has the lowest breakdown voltage for a certain value of $pd$, which depends on the gas medium and the material of the cathode. $V_B$ increases as $pd$ increases on the right side of the Paschen curve and increases with respect to the lowest breakdown value on the left side of the Paschen curve. For most gases, $V_B$ is a single-valued function of $pd$, but in Helium gas, for certain $pd$ below about 1.7 Torr-cm, breakdown may take place for three different values of the breakdown voltage [1]. While there is no complete quantitative explanation of the multi-valued behavior of the Paschen curve, it is shown that in large extent this behavior is connected to the energy dependence of the electron emission yield for ion impact onto the cathode surface and the ion impact ionization of buffer gas atoms [1,8,9]. Modelling has shown that the following processes are the main contributors of the
particular shape of the Paschen curve in helium at low pressures [3]: the dependence of the (ion-induced) secondary electron emission yield on the ion energy, the appearance of ion impact ionization of the gas at high electric fields, and the secondary electron emission from the cathode due to fast neutral atoms. To test these modelling results, previous experiments have been conducted with a copper cathode and anode. Modelling also demonstrated that backscattering of electrons from the anode can influence the breakdown voltage at low pressures [3]. However, there have been no systematic experimental studies of those effects.

In this work, systematic experiments were conducted using the same copper cathode and a variety of materials for the anode. This was done to demonstrate the effect of the anode material on the breakdown in low-pressure helium gas. This technique helped avoid variation of the breakdown conditions due to processes not connected to the influence of the anode and to study only the effect of the anode’s material on voltage breakdown in low-pressure helium gas. In the experiments, the following materials were used for the anode: copper, aluminum, stainless steel, graphite, platinum-plated aluminum, and gold-plated aluminum. In the last two cases, 300 nm platinum and gold layers were used.

2. Experimental setup
In the experiments, an automated system for measurements of Paschen curves, shown in figure 1, was used [10]. A wineglass discharge tube is shown in figure 2. The discharge tube had two flat, disk-shaped electrodes facing each other at a variable distance from 2 to 20 mm. Most experiments were conducted at distance of 5 mm between electrodes. The cathode was made from copper and was 50 mm in diameter. The anode has the same diameter, but was made from different materials. In this work, experiments were conducted with copper, aluminum, stainless steel, graphite, platinum-plated aluminum, and gold-plated aluminum anodes.

![Figure 1. An automated system for production of reliable Paschen curves over extended range of pd.](image1)

![Figure 2. A wineglass discharge tube. Distance between cathode and anode is 2 mm (as shown).](image2)

The experiments were conducted in two regimes. In the first regime, for a certain $pd$, voltage between the cathode and anode was slowly increased from zero to breakdown voltage. In the second regime, for a certain voltage between the cathode and anode, gas pressure was slowly increased from a value without breakdown up to breakdown value. The first regime was suitable for investigation of single-valued parts of the Paschen curves, while the second regime allowed for studies of the multi-valued Paschen curves, and was most suitable for the research conducted in this work. The Paschen
curve for any particular anode material was measured ten times and all curves show below were each averaged over ten curves.

3. Results of the experiments and discussion

Results of measurements of the left sides (lower $pd$) of the Paschen curves for the copper cathode and the different (copper, aluminum, stainless steel, graphite, platinum-plated aluminum and gold-plated aluminum) anodes are shown in figure 3. It can be seen that all curves, with the exception of graphite, generally had similar behavior. The curve for graphite is substantially shifted to the right (a much higher $pd$) and has a more pronounced multi-valued section. This general behavior may be explained as follows. Anode surfaces may have substantial reflection of electrons with energies of several hundreds (thousands) of electron-volts. Those electrons for the lower $pd$ range of our data arrive at the anode from the cathode without a substantial energy loss in contrast to similar electrons for the far right side of the Paschen curve (not shown in figure 3), which have more collisions with atoms in the discharge gap. As a result, the far right side of these Paschen curves would only weakly depend on the anode material. Electrons reflected from the anode participate in the ionization processes in the discharge volume, making the breakdown simpler. As the reflection is somewhat different for different materials, the Paschen curves are not exactly the same for different anodes. The graphite surface has a porous structure. This leads to the suppression of the reflection of electrons from the graphite surface and, as a result, to more difficult ionization of helium. This explains to the breakdown at a higher $pd$ and the pronouncement of the multi-valued section of the curve. Experiments also demonstrate that an insufficient cleanliness of the anode can lead to substantial modification of the Paschen curve.

A higher manifestation of the multi-valued part of the Paschen curve allows, for example, one to demonstrate experimentally the various breakdown voltages at that part of the curve. In figure 4, the $pd$ value was first held at 1.6 Torr-cm, while the voltage between the cathode and anode was slowly increased from zero to about 400 V, where breakdown occurred. In a second experiment, for $pd$ of near 1 Torr-cm, voltage between the cathode and anode is increased from zero to 1.5 kV. Then, the $pd$ value was increased without breakdown from 1 Torr-cm to 1.6 Torr-cm. Afterwards, decreasing the voltage eventually led to breakdown at about 1.2 kV. This somewhat paradoxical behavior was a
direct manifestation of the multi-valued Paschen curve. Note that reflection of electrons from the plasma volume walls is important in gas discharge physics. For example, this effect may have profound influence on probe measurements [11].

![Paschen Curve Diagram](image.png)

**Figure 4.** Plot of 2 experiments demonstrating multi-value breakdown points for a graphite anode accessed by (1) increasing and (2) decreasing the applied voltage.

4. Conclusions
An experimental study of the electric breakdown for the plane–parallel electrode configuration using a variety of anode materials demonstrates that material of the anode can substantially affect the measured Paschen curve. This effect is especially pronounced at the left part of the Paschen curve in helium gas, causing the curve to be multi-valued. This indicates that for a certain pressure and a specific gap between the cathode and anode there are three distinct breakdown values of voltage. It was experimentally demonstrated that the form of the Paschen curve might strongly depend on the material of the anode and the cleanliness of the anode surface. This may be explained by the reflection of electrons at the anode surface.

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