Electrical Breakdown in an Argon/Titanium Hollow Cathode Gas Discharge

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Abstract: According to Paschen's law, the breakdown voltage of a gas discharge is a function of the product of gas pressure and electrode separation. However, in inhomogeneous electric field configurations or in microscale gaps additional parameters alter the Paschen curve. Here we present investigations on the breakdown of a DC gas discharge in a titanium hollow cathode (HC) with argon gas.

1. Introduction

The relation between breakdown voltage V_B of a gas discharge, gas pressure p and electrode gap d has first been approximated by Townsend [1]. His formula yields the amplification of the electron current by the first and second Townsend process:

$$\frac{I_A}{I_C} = \frac{e^{\alpha d}}{1-\gamma\left(e^{\alpha d}-1\right)}. \qquad (1)$$

I_C is the electron current emitted from the cathode, I_A is the electron current to the anode, α is the first Townsend coefficient, yielding the number of electron/ion pairs per distance produced by a free electron by impact ionization. Thus α depends mainly on the ionization energy of the gas. The second Townsend coefficient γ delivers the number of secondary electrons released by an impinging ion on the cathode. Thus it depends mainly on the work function of the cathode material. Equ. (1) shows that for

$$\gamma\left(e^{\alpha d}-1\right)=1 \qquad (2)$$

the current amplification approaches infinity, which can be interpreted as a condition for the breakdown or ignition of an autonomous discharge. In case of a homogeneous electric field $E = V_D/d$, with V_D being the voltage applied, the following condition for the breakdown voltage V_B can be derived:

$$V_B = \frac{Bpd}{\ln(Apd) - \ln[\ln(1+1/\gamma)]}. \qquad (3)$$

A and B are constants depending on the kind of gas. This is the well-known Paschen law [2]. So theoretically V_B is a function of pd, but more precise investigations have shown that the dependence of V_B on p and d is not always that simple [3]. This is especially the case for

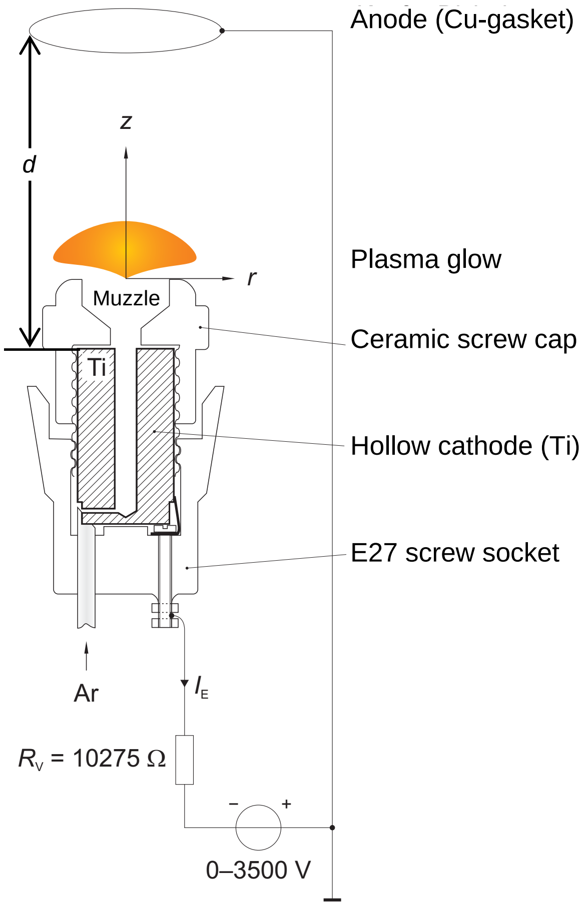


Fig. 1: Schematic of the set-up with gas feed, electric circuit and detached glow above the "muzzle".

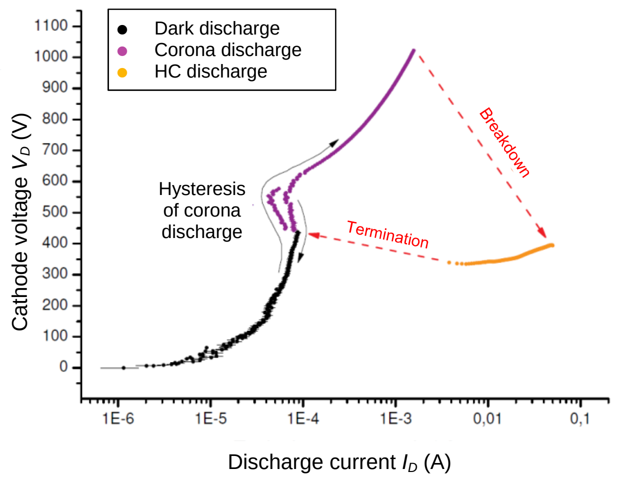


Fig. 2: Voltage-current characteristic of the hollow cathode (HC) with the three characteristic modes: dark discharge (black curve), corona discharge (purple curve) and HC discharge (orange curve) which corresponds to the discharge mode with the highest current. p = 0,316 mbar and a distance between HC and anode ring of d = 87 mm.

very small distances between the electrodes [4].

2. Experimental set-up and results

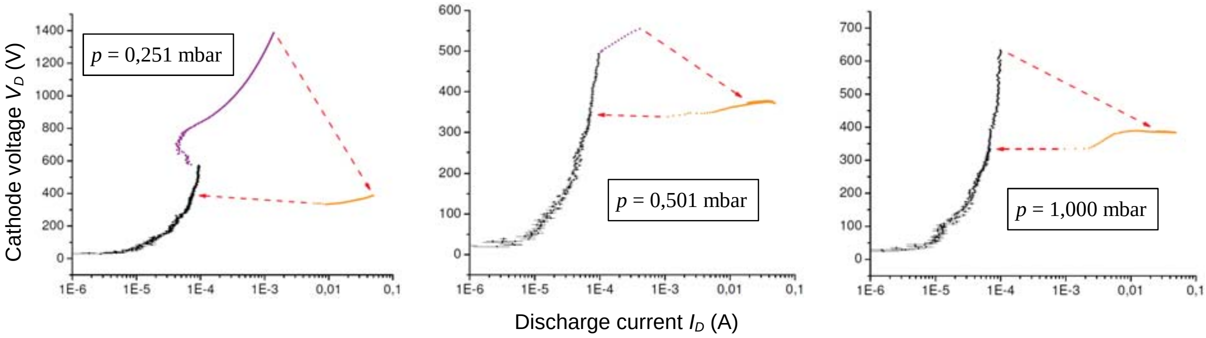
The hollow cathode (HC) system consists of an annular titanium cylinder with a length of 40 mm, an outer diameter of 22 mm and a concentric cylindrical bore of 5 mm diameter and 37 mm length [5,6] (see Fig. 1). The Ti-cylinder is embedded in the porcelain screw cap of a conventional fuse, screwed into a standardized Edison E27 porcelain screw socket. A bore of 1 mm diameter serves for the employment of the working gas (argon) from the screw socket into the HC. Into the socket the working gas enters through a PTFE-tube with an inner diameter of 3 mm. Above the screw cap (the "muzzle") a vertically movable copper ring is mounted (a Cu-gasket), which acts as grounded anode for the HC and as substrate holder. Its distance from the Ti-cylinder cathode is called *d*. The electrical connection of the socket is performed through another screw by which the Ti-cylinder is negatively biased in a range of V_0 = 0-3,5 kV through a load resistor of 10275 Ω.

Fig. 2 shows an example of the voltage-current characteristic of the HC for a pressure of *p* = 0,316 mbar and an electrode distance of *d* = 87 mm. It shows the general behaviour of the discharge for pressures below 0,6 mbar. With increasing voltage the discharge

(a) **(b)**

Fig. 3: (a) Corona discharge, (b) hollow cathode discharge above the "muzzle", d = 87 mm.

first passes through a dark discharge region (black curve), later on transforming into a purple glowing corona discharge (purple curve – see also Fig. 3(a)), until breakdown occurs and the intensive yellowish glowing HC discharge mode starts (shown by the orange curve in Fig. 2 – see also Fig. 3(b)). There is a very strong hysteresis between breakdown of the HC discharge, which here occurs at $V_B \cong 1050$ V, and its termination and return to the corona discharge mode. After ignition, V_D drops to about 380 V. By reducing the voltage V_D before ignition we see also a small hysteresis in the corona characteristic (pink curve). Fig. 3 gives an impression of the two visible discharge modes of the HC. Above p = 0,6 mbar, no corona discharge appears, but the dark discharge evolves directly into the HC discharge. Fig. 4 shows a selection of three voltage-current characteristics for increasing pressure for p = 0,251, 0,501 and 1,000 mbar. In the last case no corona discharge occurs anymore.



(a) **(b)** **(c)**

Fig. 4: Voltage-current characteristics of the hollow cathode for three different gas pressures, d = 87 mm. The black curve signifies the range of the dark discharge, the corona discharge range is shown by the purple curve, and the HC discharge by the orange curve.

As previous investigations have shown, the HC mode is strongly different from the corona discharge mode also concerning the light emission which then is mainly determined by sputtered titanium from the HC cylinder [5,6]. It was also observed that the localized brightly glowing zone (Fig. 3(b)) can detach from the "muzzle" of the HC to freely float above it [6].

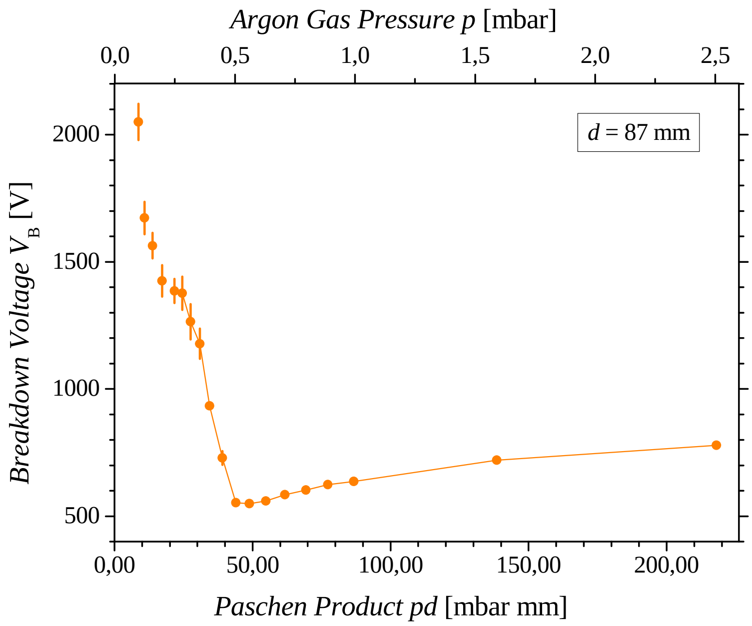


Fig. 5: Paschen curve of the hollow cathode discharge. The minimum of the breakdown voltage lies between 0,5 and 0,6 mbar. For low pressures the breakdown voltage fluctuates strongly which explains the relatively large error bars.

But this effect appeared only after several minutes when the HC was heated up by the discharge.

The Paschen curve (see Fig. 5) was compiled from measurements of breakdown patterns for constant electrode separation d = 87 mm, where the discharge voltage V_D was increased linearly in steps of 5 V at a speed of 250 ms/point. 10 – 20 breakdown patterns were measured for each data point, covering a range of 0,1 – 2,5 mbar. For each pressure value several breakdown curves were measured until thermal equilibrium was reached and the breakdown voltage stopped drifting. From the last 20 breakdown curves the breakdown voltages were derived and the arithmetic mean was taken. For pressures above 1 mbar the breakdown voltage was constant so that 10 breakdown curves sufficed for a good statistical mean value. Fig. 5 shows the resulting curve. As usual the shape of the breakdown pattern changes as the pressure passes through the Paschen curve minimum, where the breakdown voltage drops to 550 V. In spite of the different geometry the characteristic shape of the Paschen curve is preserved also here.

Acknowledgements

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