Pulsed breakdown of interelectrode gaps

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We present data on the pulsed breakdown voltage measured in some gaps filled with helium. We have examined the gap geometries that are interesting from the viewpoint of open discharge physics. The influence of reflection of fast electrons from the anode and the potential sag through the anode grid cells is determined. The times of breakdown formation have been calculated, as well as the distribution of ions over the interelectrode gap for the case of a strong electron runaway.

Nowadays, considerable attention is being paid to the gas-discharge processes under conditions of electron runaway. Usually, such conditions correspond to the far left-hand branch of the Paschen curve. However, under the action of pulsed voltage the electron runaway can be obtained under conditions corresponding to the right-hand branch of this curve too. In such a case the gas in the gap undergoes multiple overvoltage. This paper continues the studies started in Ref. 1. The aim of these studies is to obtain additional information about physics of the open discharge that efficiently generates electron beams in medium-pressure gases. This discharge arises at the stage of fast switching, and its parameters are largely determined by the processes proceeding at the breakdown stage.

The breakdown by the Townsend mechanism is known to depend on the processes not only in gases, but also on the electrodes. In particular, reflection of fast electrons from the anode back into the interelectrode gap markedly shifts the discharge voltage–current characteristic.[2] In the case of a grid anode, the effect of electron reflection becomes weaker. However, significant roles are played by the potential sag through the anode grid cells and the UV irradiation of the cathode from the area behind the anode due to the radiation generated at propagation of the fast-electron beam from the discharge gap.[1,3] This paper considers the effects of the electron reflection and the potential sag on the breakdown in helium.

The technique for measurement of the breakdown voltage U_{br} dependence on the product pd (where p is the gas pressure and d is the interelectrode gap distance) has been described in detail in Ref. 1. The voltage pulse applied to the cathode $U(t)$ had the following parameters: the rise time up to 0.8 of the maximum value is ~60 ns, almost flat top of 2 μs duration, and a drop with the time constant of 3.1 μs. The cathode was isolated from the anode with a diaphragm, which prevented breakdown along the long electric field lines.

The fact of breakdown was fixed by appearance of the gas glow, which had a threshold character with respect to the voltage. As was shown in Ref. 1, visual recording of the breakdown is more accurate than the oscilloscopic method. The breakdown always occurred within the flat top of the voltage pulse and never at its drop.

1. To exclude reflection from a plane anode, the latter was made as a stack of safety razor blades interlaid by 50-μm foil pieces (version 2 in Fig. 1). In this case, the field in the gap between the cathode and the anode was virtually homogeneous. The design of the discharge chamber allowed us to visually observe the breakdown and the shape of the discharge in the gap. It turned out that at the threshold voltage the breakdown was initiated by the open discharge occurring all over the open cathode area. The measurements of $U_{br}(pd)$ were conducted under conditions of rare pulses (the pulse repetition frequency less than 1 Hz). The results are depicted in Fig. 1, which also presents, for a comparison, the data obtained in Ref. 1. It can be seen that the absence of electron reflection from the anode at a low helium pressure has markedly shifted the breakdown curve $U_{br}(pd)$ to the right (roughly twice by pd).

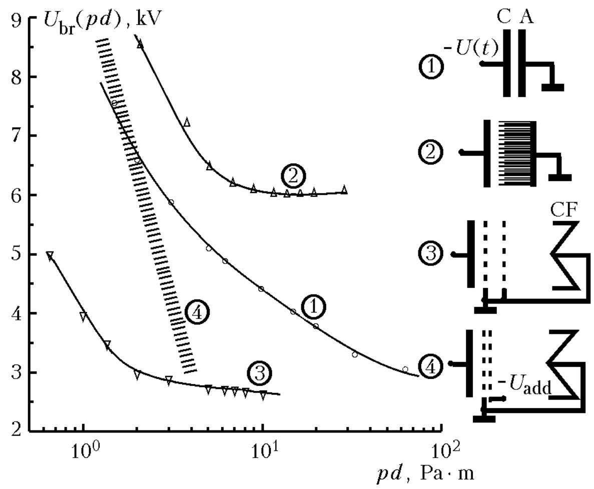

Fig. 1. Measured breakdown voltages for four versions of the discharge gap: versions 1 and 3 are borrowed from Ref. 1; C is the cathode, A is the anode, CF is the electron beam collector.

At the medium and high pressures, the difference assumes the qualitative character, which is to be explained yet. It is likely connected with the fact that curve *1* was obtained at breakdown by the high-current channel,[1] while curve *2* was obtained at a single breakdown.

2. The effect of the potential sag on the breakdown of the gap with the grid anode was studied in the discharge chamber presented by version *4* in Fig. 1. An identical grid was placed in the anode shadow at the distance of 0.25 mm from the anode. The dc negative voltage U_{add} was applied to this grid through a 3.3 kΩ resistor. The potential sag at the center of the anode grid cells was estimated by the equations from Ref. 4 as 6.7% of $U(t)$, and the sag depth was found to be (0.1% of $U(t)$) 2 mm. However, the experiments showed that the effective sag depth is much shorter because the potential is screened by the volume charge of ions produced here and having no time to leave this zone.

The effect of the potential sag can be determined by estimating the current amplification factor in the sag region K_{sag}:

$$K_{sag} \approx \frac{w(d)}{\alpha}\ [e^{\alpha l} - 1] = K(d)\ \left[e^{\alpha l} - 1\right]. \qquad (1)$$

Here $w(d) = dK(x)/dx|_{x=d}$ is the density of ionizations in the electron avalanche at the anode; α is the mean Townsend coefficient at the sag depth l. Assuming l equal to the doubled size of the anode grid cell, at the gap voltage of 10 kV and $p = 4$ kPa, we obtain $K_{sag} \sim 4$, whereas $K(d) \approx 0.4$ (Ref. 5). Thus, current amplification in the sag region turns out many times higher than in the cathode–anode gap; therefore, the ionization processes in the sag region must determine the breakdown of the gap d.

The tests of version 4 have shown that the breakdown voltage U_{br} is very sensitive to the potential across the control grid U_{add}. This is especially pronounced at low helium pressures, when U_{br} increases by a few hundreds volts at U_{add} = 10–20 V. The breakdown voltage increases monotonically with increasing U_{add} up to some value, at which the discharge is likely initiated between the grids. This discharge leads to the inverse effect: decrease of U_{br} to values much lower than at $U_{add} = 0$.

Since the voltage of discharge initiation between the grids has a wide spread and depends on the separation between them, the values of U_{br} are widely spread too. For this reason, the obtained dependence $U_{br}(pd)$ is drawn as a band and gives only qualitative idea about the effect of the control potential U_{add} on the breakdown. Nevertheless, it can be stated that at low pressures the potential sag through the anode grid cells is a decisive factor for the breakdown of the cathode–anode gap. But as the gas pressure increases, the sag role decreases drastically because of the fast increase of the intensity of UV irradiation from the area behind the anode. It is just these circumstances that determine the shift of curve *3* in Fig. 1 with respect to curve *2*.

3. Describe quantitatively the process of breakdown in the studied cases. According to the common knowledge,[6] the breakdown by the Townsend mechanism occurs in two stages. At the first stage (the stage of avalanche generation), the needed amount of the volume charge of ions is accumulated in the gap as a result of the avalanche effect. At the second, faster phase, the ionization waves are generated, and they provide for the needed conductivity of the gas in the electrode gap. At the phase of avalanche generations, the density of the electron current at the cathode at the time t, $j_e(t)$, and the volume positive ion charge $Q_+(t)$ can be presented as follows:

$$j_e(t) = j_0 \exp\{[\gamma K(d) - 1]\ t/\tau\},$$

$$Q_+(t) = \int_0^d \{j_+(x,t)/v_+(x,t)\}\, dx, \qquad (2)$$

where j_0 is the density of the initial current; γ is the coefficient of electron emission from the cathode; $K(d)$ is the current amplification factor in the interelectrode gap, it is equal to the number of electrons in the avalanche having passed the way from the cathode to the anode d (without the primary electron); τ is the characteristic time equal to the mean time of ion drift to the cathode; $j_+(x,t)$ and $v_+(x,t)$ is the ion current and the ion drift speed at the distance x from the cathode. The ratio t/τ determines the number of avalanche generations.

It is obvious that the greater is the number of the initial electrons and the higher is the current amplification factor $K(d)$ in the gas, the shorter is the first phase. Its duration is equal, in fact, to the duration of the breakdown formation t_f. In this case

$$Q_+(t_f) = \left[\gamma K(d) - 1\right] \int_0^{t_f} j_+(0,t)\, dt = 2\varepsilon_0 b U_{br}/d\ , \qquad (3)$$

where ε_0 is the dielectric constant; b is the degree of the external field distortion by the volume ion charge, when the ionization wave arises in the gap d ($b \sim 0.1$–0.2 [Ref. 6]). From Eq. (3), with the allowance for Eq. (2), we obtain

$$t_f = \frac{\tau}{K(d) - 1/\gamma} \ln\left(\frac{2\varepsilon_0 b U_{br}}{\tau j_0 d}\right). \qquad (4)$$

At the exponential increase of electrons in the avalanche, the volume ion charge is mostly concentrated near the anode and τ is equal to the time needed to an ion to pass the interelectrode gap T_+. However, under the electron runaway conditions the avalanche has a rather complex evolution, especially, in the beginning of the path.[5] Therefore, the pattern described is valid only at $K(d) \geq 10^2$. At a smaller $K(d)$ we can expect that both the ion distribution in the gap and the value of T_+ will be different. Let us find them.

At a weak distortion of the external field by the volume ion charge (which is valid for the phase of avalanche generations), the ion density is described by the following equation[7]:

$$n_+(x,t) = \gamma \int_0^l w(x+\xi)\, n\left(0, t - \frac{\xi}{v_+}\right) d\xi + \frac{j_0}{v_+}\left[K(x+l) - K(x)\right],$$

where $l = v_+ t$ at $t < (d - x)/v_+$; $l = d - x$ at $t \geq (d - x)/v_+$; $w(x) = \mathrm{d}K(x)/\mathrm{d}x$. The value of $K(x)$ can be calculated by the method described in Ref. 5. The results calculated at weak current amplification $(\gamma K(d) - 1 = 0.3)$, when the peculiarities in the evolution of the avalanche of runaway electrons are most pronounced, are shown in Fig. 2.

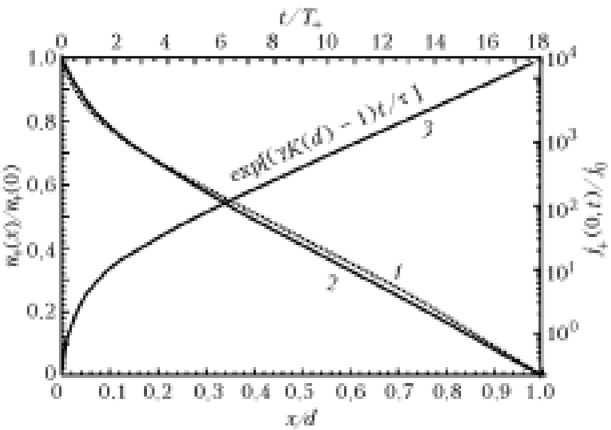

Fig. 2. Calculated ion density distribution over the length of the interelectrode gap at two moments in time: $j_e(t_1)/j_0 = 10$ (*1*); $j_e(t_2)/j_0 = 10^4$ (*2*), and the electron current density at the cathode as a function of time (*3*) at the following parameters: helium density of $1 \cdot 10^{24}$ m^{-3}, $d = 2$ mm, $U = 20$ kV, $\gamma = 0.6$, $T_+ \approx 53$ ns, $\gamma K(d) - 1 = 0.3$.

It can be seen that the highest ion density is concentrated near the cathode, and therefore the time constant τ is equal to only the half time of ion propagation from the anode to the cathode T_+.

The material presented allows us to estimate the time of breakdown formation t_f from Eq. (4) under the experimental conditions described in Sect. 1. According to data from Refs. 8 and 9, for curve *2* in Fig. 1 the logarithm is equal to 25–30, and T_+ varies from ~10 ns at the left end and to ~ 100 ns at the right end of the curve *2*. Finally, we have that t_f is roughly equal to the half duration of the voltage pulse t_p at the left end and $t_f \ll T_+ \ll t_p$ at the right end of the curve *2*. For curve *1* at the right end, we obtain $t_f \sim T_+ = 200$–300 ns, which also is much shorter than t_p. The difference $t_p - t_f$ is equal to the statistical delay time of the breakdown t_{st}. Consequently, in our case it is ~ 2 μs at the cathode field strength of 30–60 kV/cm, and this result is in a good agreement with the data from Ref. 9.

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