Analysis of electric field redistribution and its effect on formation of runaway electron beam at the breakdown stage of a strongly overvolted gap

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The possibility of electron beam formation during breakdown in a gas-filled diode for nitrogen at the atmospheric pressure is analyzed theoretically. The propagation speed of the plasma channel in the gap and its conductance is estimated for different conditions. It is shown that the distortion of the electrical field in the interelectrode gap results in formation of the conditions sufficient for generation of runaway electrons. The calculations have demonstrated that the experimentally obtained current switching rates could be explained only by formation of highly conducting plasma channels at the early stage of the breakdown. The estimates of the switching rates within the plane model of the plasma front give the propagation speeds of the plasma front that are several orders of magnitude lower than those observed experimentally.

Introduction

The effect of electron runaway in gases was predicted by Wilson in 1925.[1] He supposed that electrons accelerate in a lighting discharge at the leader front. Electrons that gain energy in a free pass at a higher rate than they lose it through interactions (both elastic and inelastic) with atoms or molecules of a gas are commonly referred to as runaway electrons.[2] The conditions of generation of runaway electrons significantly depend on the gas type and pressure, as well as the interelectrode gap length and geometry. It is usually believed that at some critical ratio E_{cr}/p (E_{cr} is the critical strength of the electric field, p is the gas pressure) a marked portion of all electrons can transit into the mode of continuous acceleration. In 1972 Babich and Stankevich[3] formulated the criterion, that for the noticeable amount of runaway electrons to appear in air at the atmospheric pressure, high fields are needed: $E_{cr}/p \sim 3$ kV/(cm·Torr). Korolev and Mesyats[2] gave the close value $E_{cr}/p \sim 4$ kV/(cm·Torr), which was calculated for nitrogen at the atmospheric pressure.

Recently,[4,5] the critical parameter E_{cr}/p was estimated from the non-local breakdown criterion, and the considerable effect of the electron multiplication process on the value of E_{cr}/p was noted. The allowance for the electron multiplication, in which secondary electrons have low energies, has led to the increase in the E_{cr}/p ratio. Thus, in Refs. 4 and 5, for helium at the atmospheric pressure E_{cr}/p depended on pd (d is the interelectrode gap); and as pd changed from 5 to 200 cm·Torr, the E_{cr}/p ratio amounted to 1.6–5 kV/(cm·Torr), while in Ref. 2 the calculation for the steady-state electron multiplication conditions gave $E_{cr}/p \sim 0.55$ kV/(cm·Torr).

The experimental investigations of the electron runaway effect were mostly carried out at a low pressure of various gases. Under such conditions, rather high current densities of runaway electron beams were obtained.[6] The study of formation of fast electrons at the elevated pressure was started in the late 1960s. The X-ray radiation generated at the atmospheric pressure by runaway electrons decelerating at the anode was found in air[7] and in helium.[8] However, till 2002 the amplitudes of the current pulse of runaway electrons at the atmospheric pressure of various gases were low. Thus, Babich, Loiko, and Tsukerman, who reviewed the basic results of investigations into the electron runaway at elevated pressures,[9] presented maximal amounts of the runaway electrons. For air at the atmospheric pressure, it is about 10^9 electrons per pulse, which at the current pulse duration of 1 ns corresponds to the amplitude of the electron beam equal to fractions of ampere behind the foil.

In 2002–2003, a series of experiments on generation of runaway electrons in air, He, and N_2 at the atmospheric pressure were conducted in the Institute of High-Current Electronics.[10–15] The experiments revealed rather high amplitude of the beam current (20–70 A in air, 200 A in helium), and the ratio $E/p = U/d$ averaged over the gap was ~0.1 kV/(cm·Torr), which is much lower than the critical value E_{cr}/p for generation of runaway electrons. To explain the results obtained, it was supposed[10,12] that the critical field occurs near the anode as the plasma cloud moves from the cathode toward the anode. Note that, in Refs. 7–15 devoted to generation of e-beams in gases at the elevated pressure, the gaps were formed by the plane anode and the cathode with a small curvature radius. In this geometry, the highest electric field was concentrated on the cathode in the region of the highest curvature.

The aim of this work is to model the conditions of filling the anode–cathode gap with plasma for nitrogen at the atmospheric pressure and at high E/p, as well as to find the gap zone with the highest electric field, where runaway electrons can be generated.

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Simulation of the electric field amplification in the 1D geometry

One of the possible mechanisms of the electric field amplification in the gap up to the critical values is the field amplification between the anode and the plasma moving from the cathode.

This approach assumes the following. The discharge occurs in the plane geometry. The plasma with the plane interface between the highly and lowly conductive regions propagates from the cathode to anode, as shown in Fig. 1. The discharge gap is divided into two zones, where zone *1* is the ionized gas (plasma) and zone *2* is the gas with low ionization. For simplicity, it is assumed that the plasma conductivity σ_1 and the conductivity of the low-ionized gas σ_2 are homogeneous in the zones *1* and *2*, respectively. On the assumption of continuous conduction current, we obtain the following overall voltage drop in the gap:

$$U_\Sigma = U_2(1 + 1/k),$$

where $k = \sigma_1/\sigma_2$. Then the field strength in the zone *2* is

$$E_2 = U_\Sigma/[(1 + 1/k)\,(d - a)],$$

where $a = a(t)$ is the length of the zone *1* at the time t. It can be seen from Fig. 2 and the equation for E_2 that, as the plasma approaches the anode, the field in the zone *2* is amplified.

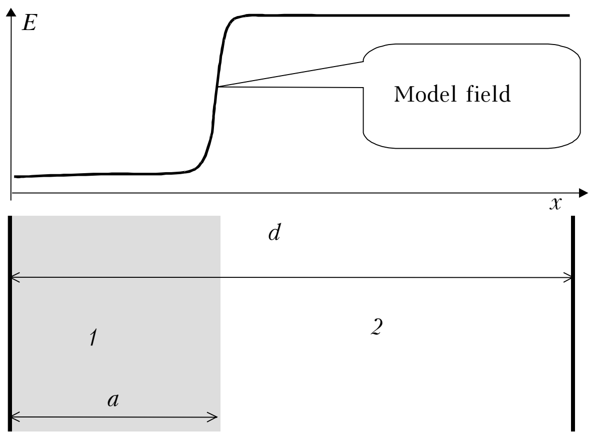

Fig. 1. Distribution of the field strength in the one-dimensional model of the plasma front motion.

Thus, starting from some time, the field in front of the propagating plasma exceeds the critical value. This means that the criterion of transition to the continuous acceleration of electrons is fulfilled and the electrons are generated in the gap. In this model, the fast-electron beam terminates, when the plasma bridges the gap and the field strength levels off all over the gap.

However, in the case at hand, the plasma propagates to the anode with the electron drift speed of the order of 10^7 cm/s at the breakdown field strengths. This speed is obviously insufficient for plasma to bridge the gap for the time of about 1 ns, as was observed experimentally.[13] To gain the agreement with the experimental data in the time needed for bridging the gap, at least a part of electrons at the beginning of breakdown must have relatively high energy. Thus, the needed speed of $\sim 1.6 \cdot 10^9$ cm/s corresponds to the electrons with the kinetic energy of ~1 keV. The one-dimensional model fails to explain the appearance of such high-energy electrons.

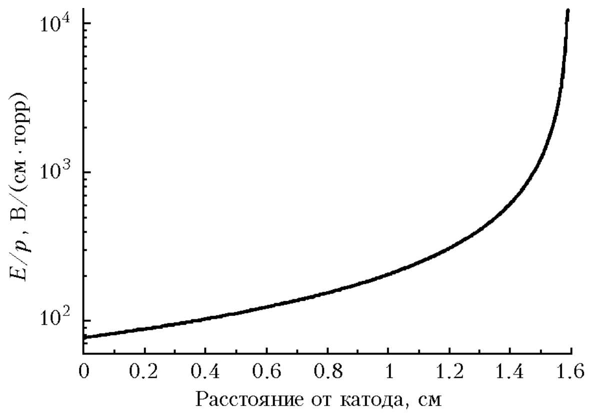

Fig. 2. Field strength in the zone *2* for the 1D model of the plasma front motion versus the distance traversed by the plasma at the discharge gap length of 16 mm.

Simulation of the electric field amplification in the pin–plane geometry

Another mechanism of the field amplification up to $E/p \gtrsim (3–4)$ kV/(cm · Torr) was studied in Ref. 16. A highly conductive axisymmetric pin-shaped channel propagates between two plane electrodes from the cathode to anode.

Let the channel at some time have the length a, as shown in Fig. 3. In this model, it is believed that the plasma conductivity in the column and inside the channel is independent of the coordinate. The gap is divided into three zones: in the zone *1* the channel has already propagated and the gas has a high conductivity σ_1; zone *2* has a strong (amplified) field near the pin tip, and its linear dimensions are comparable with the curvature radius of the pin tip; zone *3* is the remaining part to the anode. The gas in this zone is weakly ionized, so its conductivity σ_2 is comparatively low.

The field strength in the three zones can be estimated by the following equations[16]:

$$\begin{cases} E_1 = E_0\beta/\left[\beta + (k-1)(1 - a/d)\right], \\ E_2 = kE_1, \\ E_3 = E_1(k + \beta - 1)/\beta. \end{cases}$$

Here E_1, E_2, E_3 are the field strengths in the zones *1*, *2*, and *3*; $\beta(a)$ is the coefficient of geometric amplification of the field near the tip of the ideally conductive channel of the same shape and length; $k = \sigma_1/\sigma_2$ is the conductivity ratio of the plasma inside the channel and near the anode; $E_0 = U/d$ is the mean field strength in the gap.

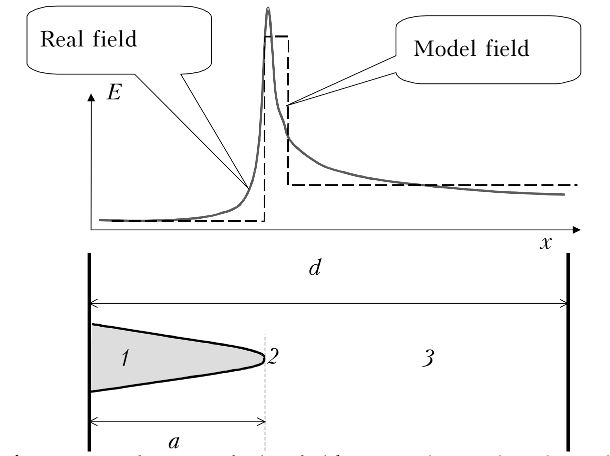

Fig. 3. Distribution of the field strength in the channel model of the plasma front motion.

Thus, it is assumed in the model that the channel propagates under the effect of the strong field in the zone *2*. Naturally, the speed of the plasma front in this model can be much higher than in the 1D model.

Estimation of parameters of the process of breakdown and generation of the fast-electron beam

As the voltage across the gap increases, the criterion of transition to the continuous electron acceleration is fulfilled on the cathode starting from the very early stage of breakdown due to the inhomogeneous plasma in the strong field zone *2*. As this takes place, the concept of the electron drift loses its meaning, and the model calls for some improvement.

The channel movement rate is no longer calculated in the drift approximation, but from the following reasoning. The most portion of the electrons falling within the strong field zone moves in the continuous acceleration mode. The rate of ionization produced by these high-energy electrons determines now the channel movement speed: in fact, it is connected with the conductivity increase in the zone *2* as a result of the intensified ionization. The electrons in the gas are assumed multiplying by the exponential law. The linear dimension of the strong field zone near the tip b is roughly equal to the tip curvature radius. Therefore, the characteristic ionization time, that is, the time, for which the conductivity in the zone *2* becomes equal to that in the zone *1*, is

$$\tau = \nu_i / \ln k,$$

where

$$\nu_i = n_a < \sigma_i \, v_e >$$

is the ionization frequency; n_a is the concentration of gas atoms; σ_i is the ionization cross section; v_e is the mean chaotic electron velocity. In this approximation, we obtain the following estimate for the channel penetration rate

$$w = \frac{b}{\tau} = \frac{b\nu_i}{\ln k} = \frac{b n_a < \sigma_i v_e >}{\ln k}.$$

The total discharge current was estimated from the equation of current continuity in the gap: $I = N j \pi b^2$, where $j = \sigma_1 E_1$. It is believed here that N channels propagate, and the mutual shielding of their field is ignored. Thus, specifying the total maximal discharge current and the number of channels, we can estimate the plasma conductivity in the channel from the experimental data.

The characteristic ionization time τ can be estimated through the energy release in the zone *2* from the relationship $\tau \sim \varepsilon_i n_c / (j E_2)$. Here $j = \sigma_2 E_2$ is the current density, E_2 is the field strength near the channel tip; ε_i is the energy for formation of one electron–ion pair in the given gas; n_c is the electron concentration in the channel.

The experiments[13–15] have shown that the runaway electron beam is formed for the time of about 1 ns or shorter, which is roughly equal to the duration of the applied voltage pulse front. Therefore, without loss in generality, we used the rough approximation of the voltage pulse as shown in Fig. 4*a*. The front length of the approximated pulse was equal to ~1 ns, and, once achieving the peak, the voltage remained constant for the infinitely long time.

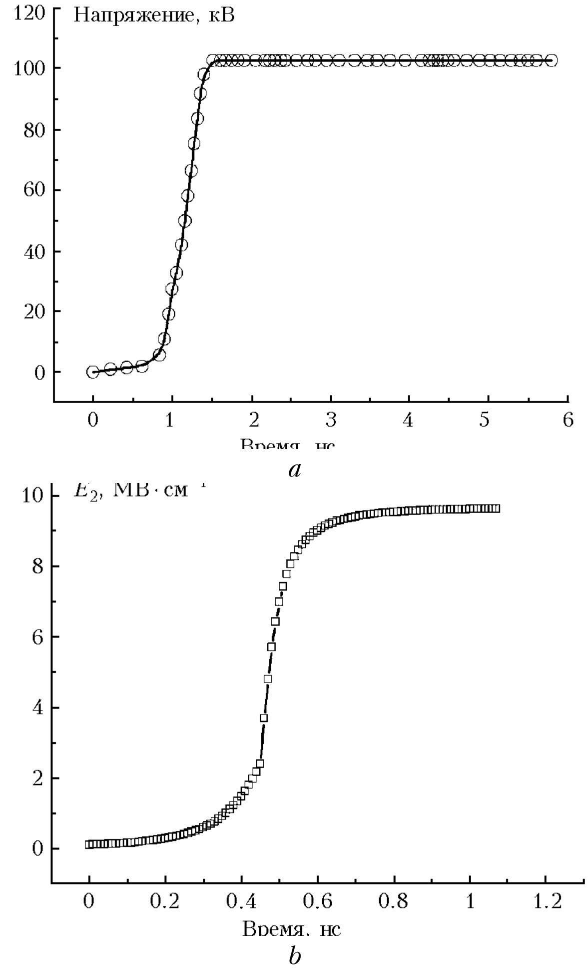

Fig. 4. Applied voltage pulse (*a*); time dependence of the field strength in the zone *2* for the channel model of the plasma front motion (*b*).

As was already mentioned, the channel grew in the amplified field E_2, therefore the self-consistent problem was solved. According to the experimental data, the total maximal discharge current was taken equal to 2.5 kA. The dependence of the field strength at the nitrogen pressure of 1 atm in the zone *2* (k = 150, b = 50 μm, $\sigma = 50\ \Omega^{-1} \cdot cm^{-1}$) plotted in Fig. 4*b* demonstrates that the field is amplified up to the needed value for the time ~0.5 ns. The drastic increase of the field strength is caused by the high value of the geometric amplification coefficient β in this zone.

The calculations have shown that the time needed for the channel to bridge the gap at k = 100–150 and b = 50–100 μm is close to 1 ns (Fig. 5). For the larger channel diameter, the time for the bridging is already several nanoseconds, which exceeds the duration of the voltage pulse front. Note that the discharge between the cathode and anode in the experiment is a volume having the form of several jets, each greater than 1 mm in diameter, and bright spots of the diameter smaller than 1 mm are observed only near the cathode.[13,14] The time, for which the field in the zone *2* achieves the value sufficient for transition of most electrons into the mode of continuous acceleration, was calculated as well. For

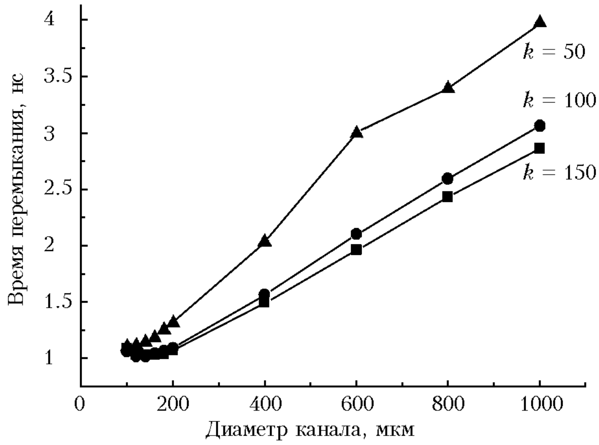

Fig. 5. Time needed to the channel to bridge the gap as a function of the channel diameter.

k = 100–150 and b = 50–100 μm this time does not exceed ~0.8 ns. The distance traversed by the channel for this time is about 10^{-2}–10^{-1} cm. This means that the criterion formulated in Ref. 3 begins to fulfill near the cathode (the length of the discharge gap is 16 mm).

Thus, upon formation of thin channels, the electric field near the cathode can exceed the critical value, and the gas ionization by fast electrons ensures fast progression of the high-conductivity plasma front. As was mentioned above, the fast electrons with the energy of ~1 keV can provide for bridging the gap in ~1 ns. The energy of the fast electrons generated in the zone *2* at the voltage pulse front does not exceed 10–20% of the applied voltage. That is, it amounts to ~10–20 keV at the maximal voltage under the conditions of Ref. 13. Note that the energy of the fast electrons at the anode is determined not only by the voltage in the zone *2*, but also by the residual voltage drop in the zone *3*, as well as the length of the zone *3*. In this case, the higher is the energy accumulated by the electrons in the zone *2*, the lower are their energy losses in the zone *3*.

Conclusions

Thus, the conducted theoretical analysis refines the mechanism of generation of a short electron beam in a gas-filled diode at the elevated pressure, which was studied in Refs. 9–15. As the voltage pulse with the steep front is applied to the gap formed by the plane anode and the cathode with the small curvature radius, fast electrons are generated due to the field amplification near the cathode. The fast electrons are supposed to provide for the progression of the plasma front with the speed of $(1–2) \cdot 10^9$ cm/s. The beam of runaway electrons is formed due to the redistribution of the electric field in the gap and its amplification in the local area on the top of the plasma front. The subnanosecond duration of the beam current pulse is determined by two factors: high speed of propagation of the plasma after reaching the critical field in the local area and the leveling of the electric field in the gap once the plasma comes to the anode.

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