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Simulation of streamer-to-spark transition in short non-uniform air gaps

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Abstract. Propagation of positive streamers in a short non-uniform gap in dry air and the evolution of plasma channels after bridging of the gap have been simulated. The dependence of the streamer-to-spark transition time τ_{br} on the mean electric field in the gap has been obtained for conditions when the transition occurs in a nanosecond time range. Calculated values of τ_{br} are in a reasonable agreement with experimental data. According to the results of the simulation, the major cause of spark formation is an increase, with time, of the electron detachment rate due to the accumulation of oxygen atoms and other active particles.

1. Introduction

The initial stage of discharge development at sufficiently high values of the product pd of the gas pressure and the gap length is the formation and propagation of ionization waves—streamers. If the mean value of the electric field in the gap $E_m = U/d$, where U is the applied voltage, is greater than the stability field E_{st} [1], streamers can cross the whole gap. In weakly electronegative gases, such as atmospheric air, the values of E_{st} for gaps with non-uniform electric field distribution (point–plane, wire–plate, etc) are several times less than the critical field E_c corresponding to the equality of ionization and attachment coefficients. It means that crossing the gap by the primary streamer does not necessary lead to breakdown. The next stage of discharge development—the evolution of the streamer channel is determined by the mean field value E_m. If E_m is noticeably lower than E_c, the mean net ionization rate is negative, so the conductivity of streamer channel and, hence, the current just after the bridging of the gap decrease with time. However, in the initially decaying plasma processes exist that tend to decelerate the decay and even to change the sign of the net ionization rate. As a result, after some time delay the decrease of current can be changed to an increase in current, leading finally to breakdown.

The first stage of discharge development in short non-uniform gaps in air—the streamer propagation has been considered in detail using both experiments and simulations (see, e.g., [2] and references therein). The processes determining the second stage—the plasma channel evolution after a streamer crosses the gap are less clear. Two major factors leading to the growth of plasma conductivity have been proposed. One, a thermal mechanism [3–5], is a lowering of the gas number density n inside the channel due to the expansion of the heated plasma. It leads to the growth of the mean reduced field E_m/n and, hence, to an increase of the ionization coefficient. Another, a kinetic mechanism [6–9], is related to the accumulation of active particles (radicals and excited molecules) changing the balance between the rates of generation and loss of electrons due to the acceleration of the detachment, stepwise and associative ionization, etc. Both of these factors act simultaneously, but their relative contributions depend on the external conditions. A noticeable lowering of the gas density may take place at times that are greater than the ratio of the streamer radius to the sound velocity. At typical streamer radii, being several hundreds of micrometres, these times are in the order of microseconds. It means that for conditions when the streamer-to-spark transition occurs in the nanosecond time range (at transition times less than 1 μs) the kinetic mechanism is dominant.

The time delay τ_{br} between the bridging of the gap and spark formation is one of the main characteristics of the streamer-to-spark transition. The values of τ_{br} strongly depend on the mean reduced electric field in the gap. The comparison of measured τ_{br} values with results of simulation could give the positive conclusion about the possibility of streamer-to-spark transition being due only to kinetic processes in the channel. The values of τ_{br} in short non-uniform air gaps have been measured in a number of works [10–13]. In most of the experiments the gap voltage during the transition was not kept constant. Recently, measurements of τ_{br} have been made in rod–plane gaps in dry air [13] using the arrangement that maintains the constant gap voltage. In the present paper, the results of a simulation of the streamer-to-spark transition in dry air, occurring in the nanosecond time range, are given. Calculated values of τ_{br} are compared with the experimental data [13].

2. The model

Positive streamer propagation in dry air at normal temperature and pressure is simulated in a point–plane gap (with the parabolic point radius $R_p = 0.2$ cm and the gap length $d = 1$ cm) using the streamer model [2]. The distribution of electric field $\boldsymbol{E}$ is given by the Poisson equation for the potential Φ as

$$\boldsymbol{E} = -\nabla\Phi \qquad \nabla^2\Phi = -4\pi\rho \tag{1}$$

where ρ is the space charge density. The concentrations n_j of plasma components (electrons, ions, radicals, excited molecules, etc) are determined in the framework of the drift-diffusion approximation

$$\partial n_j/\partial t + \nabla(n_j\mu_j\boldsymbol{E}) = J_j + S_j \tag{2}$$

where μ_j are the mobility coefficients for charged particles of sort j, the sources J_j are the sums of contributions of local kinetic processes: ionization, attachment, detachment, ion–ion and electron–ion recombination, excitation, dissociation and ion–molecule reactions. The values of the rate constants of these processes are taken as functions of the local value of the reduced electric field (the validity of this approximation is discussed, e.g. in [14]). Terms S_j in the equations for electrons and positive ions describe the generation of precursor charged particles ahead of the streamer front due to volume photo-ionization by radiation of the streamer head.

The model also includes the equations for the gas temperature T_g and the vibrational energy ε_v of nitrogen molecules:

$$\frac{n}{\gamma-1}\frac{\partial T_g}{\partial t} = \eta_T jE + \frac{\varepsilon_v - \varepsilon_{v0}(T_g)}{\tau_{VT}} \tag{3}$$

$$\frac{\partial\varepsilon_v}{\partial t} = \eta_V jE - \frac{\varepsilon_v - \varepsilon_{v0}(T_g)}{\tau_{VT}} \tag{4}$$

where $\gamma = 1.4$ is the specific heat ratio, η_T and η_V are the fractions of energy input transferred to gas heating and to vibrational excitation of N_2 molecules, j is the current density, τ_{VT}^{-1} is the rate of vibrational–translational (VT) relaxation, $\varepsilon_{v0}(T_g)$ is the equilibrium value of ε_v. Equation (3) describes gas heating in the isochoric process typical for the short times of the streamer-to-spark transition. The vibrational temperature of the oxygen molecules is taken to be equal to T_g, because of their relatively quick VT relaxation.

Simulation of streamer dynamics has been performed using both two-dimensional (2D) (axially symmetrical) and one-dimensional (1D) streamer models. In the latter case a streamer is assumed to have a cylindrical form, the value of the streamer radius R_s being an external parameter of the model. The results of 2D simulations for the range of applied voltages $U = 19$–25 kV have shown that the streamer form is close to a cylinder. It allows one to consider the streamer-to-spark transition in the assumption of constant (along the channel) streamer radius. With an increase of the applied voltage there is a growth of the streamer radius R_s (from 0.02 to 0.04 cm) and current I, the concentrations of plasma components in the streamer channel being practically independent of U (analogous to the case of sphere–plane gaps considered in [2]). At the appropriate choice of R_s the results of 1D and 2D simulation of streamer propagation agree.

Evolution of the electric field E and the current I along the channel axis z may be described by the system of telegraph equations [1]. In the case when the applied voltage is independent of time this system is written as

$$\frac{\partial\Phi}{\partial z} = -E(z,t) = -\frac{I(z,t)}{\Sigma(z,t)} \tag{5}$$

$$\frac{\partial I}{\partial z} = -C\frac{\partial\Phi(z,t)}{\partial t} \tag{6}$$

where Σ and C are the conductivity and capacity per unit length. Equations (5) and (6) together with equations (2)–(4) are used for the simulation of the channel dynamics after streamer arrival at the cathode.

After the positive streamer head has contacted the cathode, a region of the cathode voltage drop is formed. In our model this region is not considered directly, its length is assumed to be infinitesimal and the following correction of the applied voltage is made: the voltage drop along the channel is taken to be equal to $U - U_{cath}$, where U_{cath} is the voltage drop in the cathode region. Note that the current density in the streamer channel during its propagation is close to the normal current density in glow discharges (about 100–300 A cm^{-2} in atmospheric air [15]). Therefore, it is natural to assume that the value of U_{cath} is close to the normal voltage drop (0.2–0.3 kV, depending on the cathode material). In our model the value $U_{cath} = 0.2$ kV was taken.

In parallel with using the equations (5) and (6) the channel dynamics after crossing the gap were considered on the base of simplified zero-dimensional (0D) approach. The kinetic equations (without the transport terms) were solved for a point inside the channel under the assumption that the electric field at this point is equal to the mean field in the channel $E_m = (U - U_{cath})/d$. Thus obtained conductivity was used for calculation of the streamer current.

As the channel evolution in nanosecond time range is considered, the gas number density n is assumed to be independent of time. At the calculation of the gas temperature using equation (3) the 'fast' heating [16, 17] is taken into account: it is assumed (as in [9]) that at the quenching of electronically excited N_2 molecules about 30% of the excitation energy goes to gas heating. The rate of VT relaxation is taken from [18].

The kinetic model includes 14 components: neutral particles N_2, N, O_2, O, NO, $N_2(A^3\Sigma)$, $N_2(a'^1\Sigma)$, $O_2(a^1\Delta)$; ions O^-, O_2^-, O_3^-, O_2^+, O_4^+; and electrons. Note that relative concentrations of positive ions of other sorts (N_2^+, N_4^+, $N_2O_2^+$) are small, because these ions quickly convert to O_2^+ and O_4^+. The rate constants of reactions including electrons are taken as functions of the reduced field E/n and the vibrational energy ε_v, the data from [19–22] are used. The rate constants of ion–molecule reactions are determined by the effective temperature $T_{ef} = (m_i T_g + mT_i)/(m_i + m)$, where m_i and m are the masses of the ion and the molecule, T_i is the ion temperature depending on E/n (see, e.g., [21]). The values of rate constants of ion–molecule reactions and processes that include radicals and excited molecules are taken from [23–26].

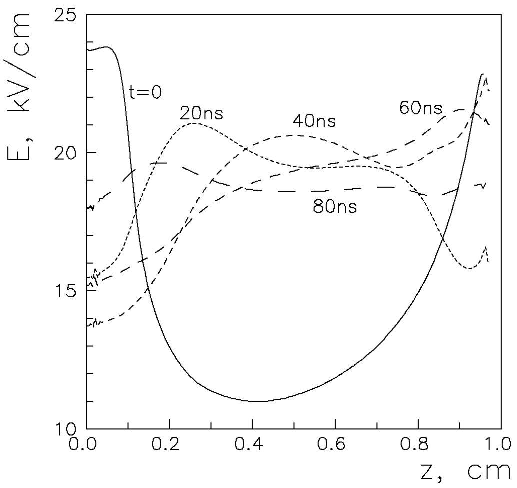

Figure 1. The electric field distributions along the positive streamer channel at various time instants for the applied voltage $U = 19$ kV. Time is counted from the moment of streamer contact with the cathode. The anode and the cathode are situated at $z = 0$ and $z = 1$ cm, respectively.

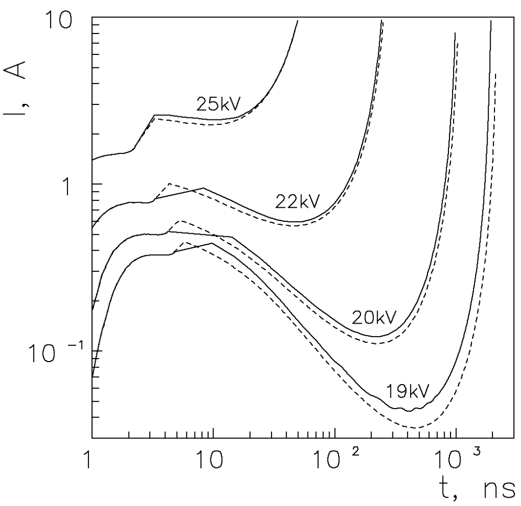

Figure 2. The electric current dependences on time for various applied voltages. Full and broken curves correspond to the results of 1D and 0D simulations, respectively.

3. Results and discussion

In figure 1 the distributions of the electric field in the channel are given at various time moments after bridging of the gap, corresponding to the applied voltage $U = 19$ kV. It is seen that after a short (in comparison with τ_{br}) time period the field distribution becomes nearly uniform. It means that the streamer-to-spark transition can be described accurately enough in the frame of the 0D approximation. Indeed, figure 2 shows that the current dependences on time calculated using 1D and 0D models agree. The forms of presented curves depend on the applied voltage (or, more exactly, on the mean electric field E_m). While at high U the current monotonously increases, at low U there is an essential, by an order of magnitude, fall of the current that is changed by the increase with the following transition to spark.

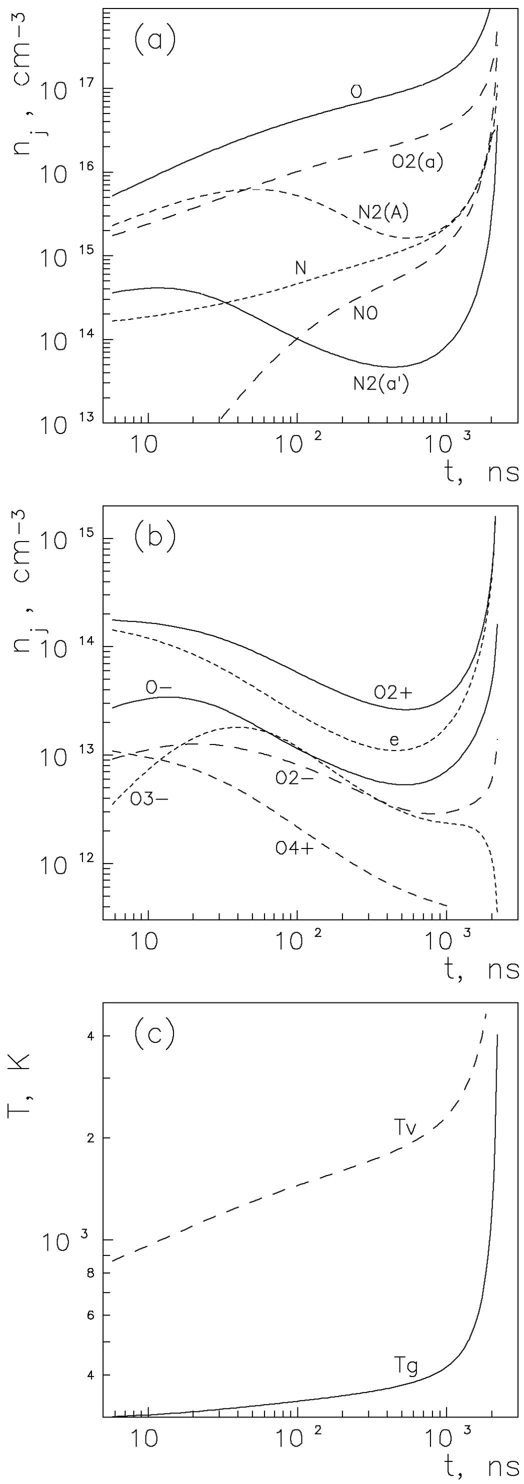

Figure 3. The concentrations of neutral (a) and charged (b) plasma components and vibrational and translational temperatures (c) for the applied voltage $U = 19$ kV.

The current profiles are determined by the kinetic processes in the channel plasma. In figures 3 and 4 the concentrations n_j of plasma components, the vibrational T_v and translational T_g temperatures obtained in the 0D approximation are presented for low (19 kV) and high (24 kV) values of the applied voltage U (for the mean electric

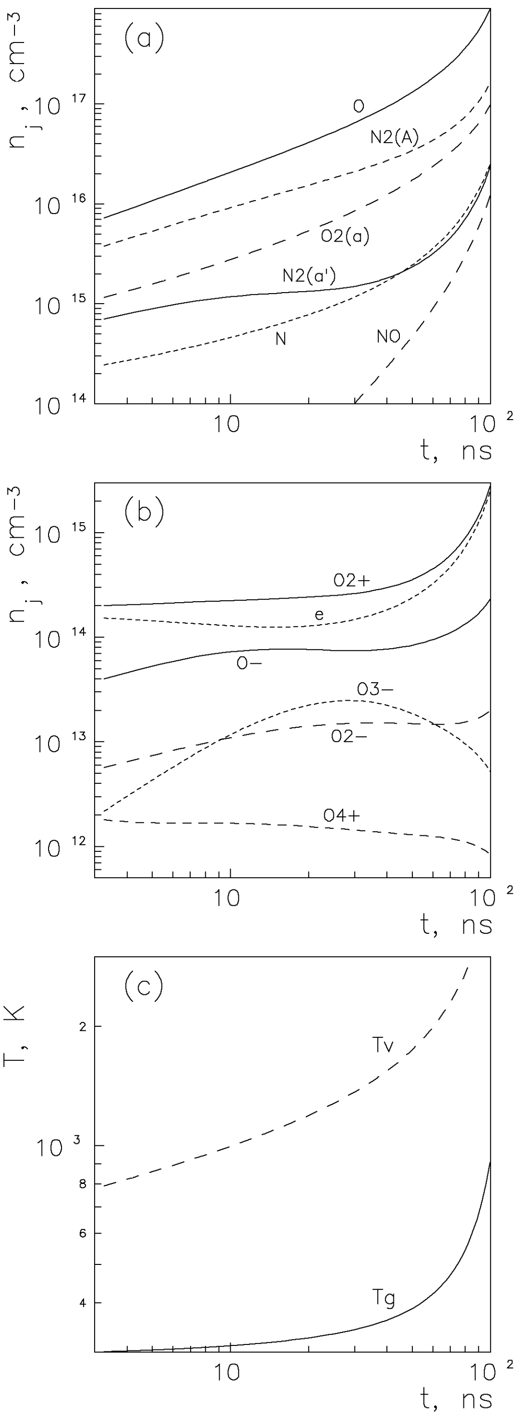

Figure 4. The concentrations of neutral (a) and charged (b) plasma components, vibrational and translational temperatures (c) for the applied voltage $U = 24$ kV.

fields 18.8 and 23.8 kV cm^{-1}). With the growth of U the ratios $n_{O_2^+}/n_{O_4^+}$, $n_{O^-}/n_{O_3^-}$ increase, due to growth of the ion temperatures. Note that the O_4^+ ions, in spite of their relatively small concentration, give a substantial contribution to the total rate of electron–ion recombination. The channel plasma is in a state of VT non-equilibrium. It is seen in figure 3(c) that at the final stage of streamer-to-spark transition the value of T_g approaches T_v, due to acceleration of VT relaxation with the growth of the gas temperature.

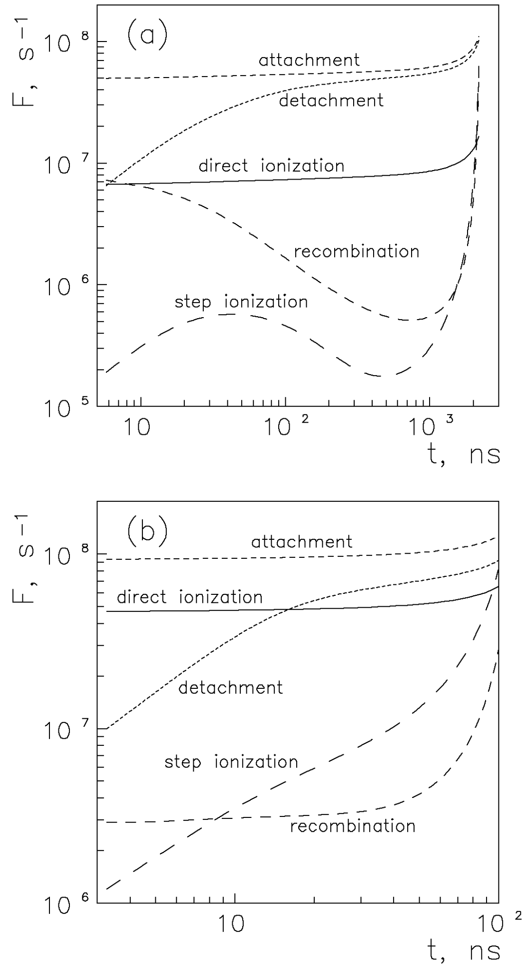

Figure 5. The rates of the processes of generation and loss of electrons for the applied voltages $U = 19$ kV (a) and 24 kV (b).

Time dependences of the concentrations show that plasma components can be divided into two groups. The concentrations of charged particles and excited N_2 molecules are quasi-stationary and non-monotonously depend on time, while the concentrations of O and N atoms, NO and excited O_2 molecules monotonously grow. Accumulation of these active particles leads to the growth of the detachment rate and a corresponding change of the electron balance.

The rates of the processes of generation and loss of electrons for two values of the applied voltage are given in figure 5. These rates are defined according to the electron number density balance equation written in the form

$$\partial n_e/\partial t = F_e n_e = (F_{dir} + F_{step} + F_{detach} - F_{attach} - F_{recomb}) n_e \qquad (7)$$

where F_{dir} is the rate of direct ionization of N_2 and O_2 molecules, F_{step} is the sum of the rates of ionization of excited molecules and radicals (mainly NO) by the electron impact, associative ionization in collisions of excited nitrogen molecules and associative ionization in collisions of O and N atoms (the latter process is effective at high gas temperatures), F_{detach}, F_{attach} and F_{recomb} are the rates of detachment, attachment and electron–ion recombination, respectively. Note that the source terms corresponding to associative ionization and detachment are not proportional to the electron

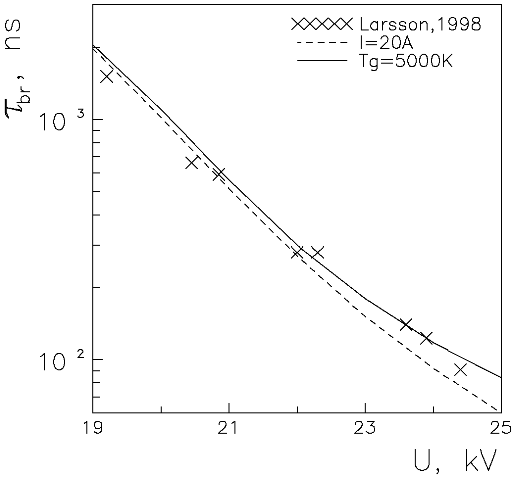

Figure 6. The experimental [13] (points) and calculated dependences of the streamer-to-spark transition time on the applied voltage. Full and broken curves correspond to the final gas temperature $T_g = 5000$ K and the final current $I = 20$ A, respectively.

number density n_e and their presentation in equation (7) as the products of n_e and F values is made only for convenience of comparison.

Initially, the net rate F_e is negative because of strong attachment (note that the relative role of recombination is small). With accumulation of the active particles the detachment rate increases, and at some time the net rate F_e becomes positive. The following growth of n_e causes an acceleration of the generation of the active particles and gas heating. Note, that during almost all of the period of streamer-to-spark transition, except its final part, the total rate of stepwise and associative ionization is much smaller than the rate of direct ionization.

In figure 6 the calculated values of the streamer-to-spark transition time τ_{br} are compared with the experimental data [13]. As the criterium of spark formation the change of the dominating ionization process from the ionization by electron impact to thermal ionization (at collisions of N and O atoms) can be chosen. The thermal ionization becomes important at gas temperatures about 5000 K. In the figure the values of time given are those required to heat the gas in the channel up to $T_g = 5000$ K. Another possible criterium of transition is an achievement of some final current, as in experiments the current may be limited by an external electric circuit. In the figure, the broken curve is shown corresponding to the final current $I = 20$ A. It is seen that at lower applied voltages both criteria give nearly the same values of τ_{br}. At higher voltages the calculated values of τ_{br} corresponding to fixed T_g are closer to the measured data.

Agreement of the results of simulation with the experimental data is an evidence of the key role of the kinetic mechanism in the streamer-to-spark transition occurring in the nanosecond time range. Note, that in this case the value of τ_{br} is independent on the streamer radius R_s, while the time of transition to spark caused by gas expansion increases with R_s. The stage of gas expansion and generation of blast waves [5] is inevitably present in the process of spark formation. However, at short values of τ_{br} this stage comes after the streamer-to-spark transition and does not determine its parameters.

The experimental data [13] and the results of simulation presented above have been obtained for dry air. The presence of water vapour radically changes the composition of the ions [25] and leads to the appearance of cluster ions such as $H^+(H_2O)_n$. In this respect it would be of interest to measure the values of τ_{br} in air with controlled water content, in order to reveal the role of plasma composition in the streamer-to-spark transition.

4. Conclusion

Simulation of streamer channel evolution after crossing the gap shows that the streamer-to-spark transition in dry air in the nanosecond time range can be caused by the accumulation of particles (mainly, oxygen atoms) active in the electron detachment process. At the final stage of the transition, the processes of stepwise and associative ionization become important. It is shown that the channel dynamics may be described with acceptable accuracy using a 0D approximation. Calculated dependence of the transition time on the mean electric field in the gap agrees with that measured in [13].

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