DEVELOPMENT OF AZIMUTHALLY NOT UNIFORM PROCESSES IN CORONA DISCHARGE IN AXIALLY SYMMETRIC GAP

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It is offered a hypothesis about connection between the experimentally observed sinuous trace of streamer with the instability of azimuthal harmonic of positive glow corona. The method of the instability analysis in linear approximation on two-dimensional mesh is described, and the calculations are carried out, which results show the instability existence. The calculations for higher harmonics corresponding to streamer bifurcation are carried out.

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INTRODUCTION

In gas discharges with electrode system close to axially symmetrical, there are observed the processes with axial symmetry violation. The simplest example is atmospheric pressure positive corona discharge between coaxial electrodes, in which non-stationary current spots at anode are localized not only along axis, but also in circular direction, and they do not envelope the whole anode cross section [1]. Also, in the discharge between the needle anode and the plane cathode, there may be observed two regions at the needle, in which the flashes happen by turn [2]. Besides, in the experiment described below, there were obtained the photos, in which streamer has sinuous form. Numerical simulations of azimuthally non-uniform processes demand to solve nonlinear equations system in three-dimensional space, which impose very high demands on computer's characteristics, and even on the powerful present computers it is practically impossible to investigate the dependences of characteristics of processes on parameters. But to investigate the linear stage of instability development of azimuthal harmonic it is enough to integrate the nonlinear equations, corresponding to axially symmetric processes, and the linear equations for perturbation, on the same two-dimensional mesh, using independence of the different azimuthal harmonics in the linear problem. In the section 1, the experimental conditions are discussed. In the section 2, it is reminded the known about the phenomenon of the pulsed positive glow corona, which, to the authors' opinion, deals with the cause of the observed azimuthal instability. In the section 3, the model, in which calculations are carried out, is described, and the results are presented.

1. EXPERIMENT

It was carried out photographing of positive corona in the streamer mode at the constant applied voltage with photo-exposition up to 2 minutes. On the photo (Fig. 1) it is revealed somewhat sinuous form of the part of streamer close to anode. It is worthy to underline that during the indicated time of exposition the streamers were created hundreds of thousands times, and each streamer have gone close to the same sinuous path.

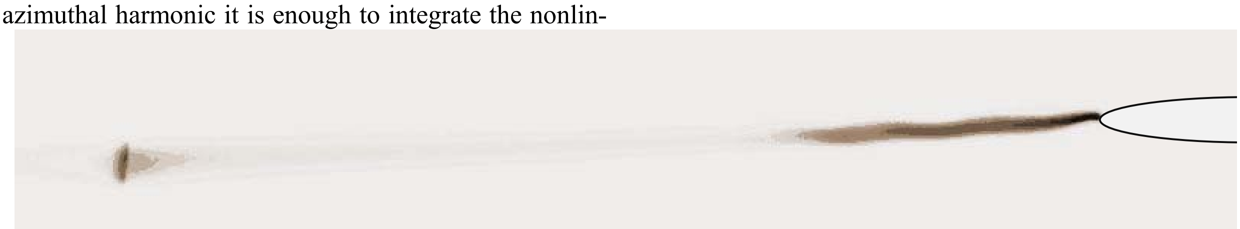

Fig. 1. The photo of streamers with exposition 2 minutes (anode is sketched)

The streamers' development from the point situated not at electrode tip, but aside, as a last resort, may be explained by the small local details of anode surface form (perhaps, by local field strengthening near surface microroughnesses). But further, in the gap, it seems, the streamer has to move to cathode by the way close to the shortest one. But the streamer during some time, as by inertia, continues to change the direction of movement, and tends to move somewhere sideways, up to the moment when it again begins to direct its movement to cathode, but further it again reveals somewhat similar to inertia, continuing to change its movement sideways, in other direction. Such behavior in atmospheric pressure conditions is very strange. Indeed, phenomena in collisional plasma are well described in the drift-diffusion approximation, with assumption about instant determination of the charged particle drift velocity by the field strength, without use of acceleration conception, which corresponds to possibility to neglect the usual mechanical inertia of tangible things movement. But to realize the most of widely known plasma instabilities such inertia is necessary, so, they cannot help to explain the observed phenomenon.

To the authors' opinion, the observed streamer behavior deals with the processes similar to ones in the so-called positive glow corona [1 - 3]. It is worthy to remind the details of this phenomenon.

2. PULSED MODE OF POSITIVE GLOW CORONA

As it is known [4], in the experiments with positive corona after achievement of the voltage value sufficient to self-consistent discharge operation, in some gas mixtures and by some experimental conditions, there are observed the pulses of total current and radiation intensity with the frequency $10^5 \ldots 10^6$ Hz. Physical mechanism of the pulses and of the oscillations, of which they come, is well made clear in the paper [3]. It is worthy to describe it, supplementing the written in [3] with some simple physical models.

For stationary discharge operation, two following processes are sufficient: (1) an emission (from the states excites by electrons moving in gas) of photons being able to ionize gas and (2) a photo-ionization (made by photon) with generation of electrons and positive ions. The electron passes the rest of gap, moving to anode and generating new photons. Also, electron can make impact ionization, which may be considered as photo-ionization at the very short distance from electron if the changed electric (accurately, electromagnetic) field of electron is being considered as photon. It is worthy to underline importance of the possibility of electrons appearance in the region farther from anode than the region of photons emission (after excitation of molecules by other electrons earlier) and following from it the possibility of new photons emission in the same region after coming of the electrons to this region during drift to anode. Absence of such possibility in the case of absence of ion-electron emission from cathode and diffusion leads to monotonous decrease of dimension of ionization process region with electron drift velocity.

An increase of the applied voltage value intensifies ionization processes with increase of electron and positive ion density, but positive ions weaken the field near needle anode, ionization processes here weaken, and new stationary mode is established with more intensive ionization process.

With further voltage increase stationary mode may become unstable and transition to pulse mode may take place. At the development beginning the oscillations close to sinusoidal ones may take place on the background of balance between ionization and particle going away. Half of period may be described as follows: in unperturbed field, surplus of electrons increases their flux away, which gradually increases positive charge (quarter-period); surplus of positive charge weakens the field and decreases ionization frequency, which gradually decreases electron number. As it is underlined in the paper [3], for the oscillations it is important the lag, on the time necessary to electrons to come out to anode, of the instant of minimum field near anode (maximal effect of field screening by positive charge) from the instant of maximal current (caused by going out of greater amount of electrons) and the lag, on the time necessary for ionization development in the near-anode region, of the instant of minimum current from the instant of minimum field.

Such oscillations reveals even with the simplest description of the process with the equations

$$\partial_t N_p + \nu_p N_p = \nu_i N_e \,, \; \partial_t N_e + \nu_e N_e = \nu_i N_e \,.$$

Here ∂_t is time derivative, $N_{e,p}$ are densities of electrons and positive ions, $\nu_{e,p}$ are the quantities reciprocal to characteristic time of removing of electrons and positive ions from the region of intensive ionization near the needle, ν_i is ionization frequency, $\nu_i = \nu_i(N_q)$, where $N_q = N_p - N_e$. The written equations may be considered as maximum simplified variant of the equations

$$\partial_t N_p + \mathrm{div}(N_p \vec{v}_p - D_p \nabla N_p) = \nu_i N_e \,,$$

$$\partial_t N_e + \mathrm{div}(N_e \vec{v}_e - D_e \nabla N_e) = \nu_i N_e \,,$$

(in which $\vec{v}_{e,p}$ are drift velocities, $D_{e,p}$ are diffusion coefficients) for the intensive ionization region after averaging by the region and neglecting of coming to it the particles from other regions. The solution is searched in the linear approximation, with taking $N = N_0 + N_1 \exp(\nu t)$, where the index 0 indicates the stationary value, and the index 1 indicates the perturbation, which is assumed small. The designations $\nu_i^{(0)}$ and $\nu_i^{(1)}$ for the values of the function $\nu_i(N)$ and its derivative with respect to N at $N = N_{q0}$ are used, and it is assumed that the inequality $\nu_i^{(1)} < 0$ holds, which corresponds to weakening (screening) of field near anode with positive charge appearing here and to relevant decrease of ionization frequency. For the stationary values one can obtain the equations

$$\nu_p N_{p0} = \nu_i^{(0)} N_{e0} \,, \; \nu_e N_{e0} = \nu_i^{(0)} N_{e0} \,,$$

with the condition $\nu_i^{(0)} = \nu_e$ of their nonzero solution existence. For the perturbation in the linear approximation one can get the equations

$$(\nu + \nu_p) N_{p1} = \nu_i^{(0)} N_{e1} + \nu_i^{(1)} (N_{p1} - N_{e1}) N_{e0} \,,$$

$$(\nu + \nu_e) N_{e1} = \nu_i^{(0)} N_{e1} + \nu_i^{(1)} (N_{p1} - N_{e1}) N_{e0} \,,$$

with the condition of their nonzero solution existence in the form of the equation $\nu^2 + \nu_p \nu - \nu_i^{(1)} N_{e0} (\nu_e - \nu_p) = 0$. For its roots the equality $(2\nu + \nu_p)^2 = D_2$ with $D_2 = \nu_p^2 + 4\nu_i^{(1)} N_{e0} (\nu_e - \nu_p)$ takes place. If negative value $\nu_i^{(1)}$ has sufficiently large modulus to ensure the inequality $D_2 < 0$ then in the considered maximum simplified system the oscillations are possible, which, however, always are dumping.

But if one takes more complex model the excitation of oscillation may appear. In particular, it takes place in the model, which is described with the equations

$$\partial_t N_x + \nu_x N_x = \nu_i N_e \,, \; \partial_t N_p + \nu_p N_p = \nu_x N_x \,,$$

$$\partial_t N_e + \nu_e N_e = \nu_x N_x \,.$$

The first of them characterizes the excitation of autoionizing states of neutral particles (index x), which disintegrates on the electron and positive ion not instantly, but with time lag (in average, on $1/\nu_x$). In such model one can obtain the equations for the stationary values

$$\nu_x N_{x0} = \nu_i^{(0)} N_{e0} \,, \; \nu_p N_{p0} = \nu_x N_{x0} \,, \; \nu_e N_{e0} = \nu_x N_{x0} \,,$$

with the same condition $\nu_i^{(0)} = \nu_e$ of their nonzero solution existence, and the equations for the linear perturbations

$$(\nu + \nu_x) N_{x1} = \nu_i^{(0)} N_{e1} + \nu_i^{(1)} (N_{p1} - N_{e1}) N_{e0} \,,$$

$$(\nu + \nu_p) N_{p1} = \nu_x N_{x1} \,, \; (\nu + \nu_e) N_{e1} = \nu_x N_{x1} \,,$$

with condition of their nonzero solution existence in the form of the cubic equation, $\nu^3 + A_3 \nu^2 + B_3 \nu + C_3 = 0$, where $A_3 = \nu_p + \nu_e + \nu_x$, $B_3 = \nu_p(\nu_e + \nu_x)$, $C_3 = -\nu_i^{(1)} N_{e0}(\nu_e - \nu_p)\nu_x$. If the equality $A_3 B_3 = C_3$ holds then the cubic equation has the pair of purely imaginary roots, $\nu = \pm i B_3^{1/2}$, and one real negative root, $\nu = -A_3$. But if $A_3 B_3 < C_3$ then the pair of complex conjugate roots has positive real part, which corresponds to excitation of oscillations.

Besides of ionization act lag the excitation of oscillations may be promoted by effect of field strengthening in the region rather farther from anode caused by the positive charge displaced directly near anode. Although this charge weakens the field in the region of its disposition, it may be so, that the field strength here achieves the values, at which the dependence of the ionization coefficient from the field strength comes to saturation, and the ionization coefficient decrease due to the field weakening by the charge is small, but in the region rather farther from anode the field is weaker, and the ionization coefficient here considerably increases (with respect to its value) with the field strengthening, and on the whole the ionization process at some stage of forming of positive charge near anode may intensify.

The written above explains nature of pulses in the electropositive gases, without drawing of negative ions to explanation. In the electronegative gases instability of the process intensifies with the movement of negative ions to anode. In the space near needle anode, electrons carry out ionization with new electrons and positive ions formation and attach to molecules and atoms with formation of negative ions. Electrons, which remain free, quickly come to anode, and in near-anode space two clouds of charged particles are formed: directly near anode it is formed the cloud of negative ions, and farther it is formed the cloud of positive ions. The cloud of negative ions strengthens electric field directly near anode and weakens it farther from anode, and the cloud of positive ions weakens field near anode. At the beginning of pulse development negative ions intensify ionization process, but approach of negative ion cloud at anode promotes ionization process dumping. During the time when negative ion cloud covers the distance the large amount of positive ions forms in the region farther from anode. When essential part of negative ion cloud comes at anode both clouds weaken electric field in the most of near-anode space and ionization process decays. The pulse dumps, and the new pulse may start after removing of positive ions from near-anode space and restoring large field strength there.

3. NUMERICAL SIMULATIONS OF AZIMUTALLY NONHOMOGENIOUS PROCESSES

In conditions of atmospheric pressure gas discharge, electron and ion motion may be considered in drift-diffusion approximation, and field may be calculated as electrostatic. Time evolution of particle densities and field potential distribution may be determined with the equations

$$\partial_t N_e - \mathrm{div}(D_e \nabla N_e + N_e \mu_e \vec{E}) =$$
$$= S_{ph} + (\nu_i - \nu_a) N_e + \nu_d N_n - \beta_{ep} N_e N_p,$$
$$\partial_t N_p - \mathrm{div}(D_p \nabla N_p - N_p \mu_p \vec{E}) =$$
$$= S_{ph} + \nu_i N_e - \beta_{ep} N_e N_p - \beta_{np} N_n N_p,$$
$$\partial_t N_n - \mathrm{div}(D_n \nabla N_n + N_n \mu_n \vec{E}) =$$
$$= \nu_a N_e - \nu_d N_n - \beta_{np} N_n N_p \quad ,$$
$$\nabla^2 \Phi = -q \varepsilon_0^{-1} (N_p - N_e - N_n).$$

Here the indexes e, p and n indicates electrons, positive and negative ions, μ are relevant mobilities, β are recombination coefficients, ν_i, ν_a, ν_d are frequencies of ionization, attachment, and detachment (number of events per time caused by single electron or negative ion, respectively), $\nu_i = \alpha \mu_e E$, where α is ionization coefficient, $E = |\vec{E}|$, $\vec{E} = -\nabla\Phi$,

$$S_{ph}(\vec{r}) = \int dV' N_e(\vec{r}\,') \nu_{ph}(\vec{r}\,') \kappa g(|\vec{r} - \vec{r}\,'|),$$

$g(r) = (4\pi r^2)^{-1} \exp(-\kappa r)$, κ is photon absorption coefficient, q is elementary charge, ε_0 is electric constant, $\nu_{ph}(\vec{r})$ is frequency of photo-ionization acts carried out in infinite space by photons emitted from the states excited by single electron moving in electric field with strength $E(\vec{r})$. The form of photo-ionization source term S_{ph} deals with two following affirmations: if frequency of photon emission from the point source situated at coordinate origin is equal to N_{ph}, then (1) for the surface placed in the point with radius-vector $\vec{r}$, the flux intensity (number of passing through surface per area per time) is equal to $N_{ph} g(r) \cos\psi$, where $r = |\vec{r}|$, and ψ is angle between flux direction (vector $\vec{r}$ direction) and direction of outer normal to the surface, and (2) absorption rate intensity (number of acts per volume per time) in the mentioned point is equal to $N_{ph} \kappa g(r)$.

Calculations are carried out for the volume restricted with ellipsoid of revolution having focuses on the axis of revolution and hyperboloids of revolution having the same axis of revolution and focuses. At electrodes-hyperboloids it is imposed the conditions of absence of diffusion flow, absence of ion emission, and existence of electron emission from cathode determined by positive ions and photons flows,

$$N_e \mu_e E = \gamma_i N_p \mu_p E + \gamma_{ph} F_{ph},$$

where γ_i and γ_{ph} are coefficients of ion-electron emission and photoemission, respectively,

$$F_{ph}(\vec{r}) = \int dV' N_e(\vec{r}\,') \nu_{em}(\vec{r}\,') g(|\vec{r} - \vec{r}\,'|) \cos\psi(\vec{r}\,', \vec{r}),$$

$\nu_{em}(\vec{r})$ is frequency of emission of proper photons (having energy sufficient to cause electron emission from cathode) from the states excited by single electron moving in the field with strength $E(\vec{r})$, and $\psi(\vec{r}\,', \vec{r})$ is angle between outer normal to cathode surface (placed in the point with radius-vector $\vec{r}$) and flux direction (vector $\vec{r} - \vec{r}\,'$ direction). At the boundary surface formed with ellipsoid, it is imposed the condition of absence of any charged particle flow to the surface or from the surface. To avoid accumulation of charged particles near this boundary it is assumed that in the elementary volumes nearest to this surface the charged particles have artificially large mobility. Potential is calculated in assumption of its fixed values at infinite hyperboloids-electrodes (one of them may be plane), and so, calculated field distribution corresponds to the case of infinite space between hyperboloids with charge in volume bounded by ellipsoid. Calculations are carried out in hyperboloid coordinates (σ,τ) connected with cylindrical coordinates (ρ,z) by the relationships $\rho = a[(\sigma^2-1)(1-\tau^2)]^{1/2}$ and $z = a\sigma\tau$, where a is half of distance between focuses. To calculate potential distribution the expansion in terms of eigenfunctions with respect to coordinate τ is made, and the obtained ordinary differential equation with respect to coordinate σ is solved with run method.

The evolution of azimuthally inhomogeneous distribution is calculated in the linear approximation. For the particle densities and potential, it is taken

$$N = N_0 + N_1\cos(m\varphi),\ \Phi = \Phi_0 + \Phi_1\cos(m\varphi),$$

where φ is azimutal angle (so that $x = \rho\cos\varphi$, $y = \rho\sin\varphi$), m is natural number (the indexes epn here are not written). The sinuous streamer path may be connected with development of the process at $m = 1$, and the processes at $m \geq 2$, in particular, may describe the streamer bifurcation. It is worthy to write some relationships used in linear approximation: for the absolute value of field strength, $E = E_0 + E_1\cos(m\varphi)$, where $E_0 = |\nabla\Phi_0|$, $E_1 = -\vec{e}_0\nabla\Phi_1$, $\vec{e}_0 = -\nabla\Phi_0/E_0$; for the perturbations (namely, for the corresponding factors at $\cos(m\varphi)$) of mobilities, $\mu_1 = \mu^{(1)}E_1$, where $\mu^{(1)}$ is the derivative of the function $\mu(E)$; for the perturbation of ionization frequency, $\nu_{i1} = \alpha_0\mu_0E_1 + \alpha_0\mu_1E_0 + \alpha_1\mu_0E_0$, where $\alpha_1 = \alpha^{(1)}E_1$; for the perturbation of the quantity $\mathrm{div}(N\mu\vec{E})$, which has the form

$$\mathrm{div}(N_1\mu_0\vec{E}_0 + N_0\mu_1\vec{E}_0) + \vec{E}_1\nabla(N_0\mu_0) + N_0\mu_0Q_1,$$

where $Q_1 = q\varepsilon_0^{-1}(N_{p1} - N_{e1} - N_{n1})$; for the perturbation of summands connected with recombination, $\beta_1N_0N_{p0} + \beta_0N_1N_{p0} + \beta_0N_0N_{p1}$. The equation for the perturbation of potential has the form $\nabla^2\Phi_1 - (m/\rho)^2\Phi_1 = -Q_1$. The diffusion coefficients are taken constant. With approach to the symmetry axis the ratios of the perturbation and the quantity ρ^m approaches the bounded values, so, it is worthy to remove the factor $(\sigma^2-1)^{m/2}$ and to rewrite the equations for the coefficients at it. In particular, for the perturbation of potential the solution is searched in the form of the expansion $\Phi_1 = \sum_\nu \Phi_{1\nu}(\sigma)\mathrm{F}_\nu^m(\tau)$ (with unknown $\Phi_{1\nu}(\sigma)$) over the eigenvalues ν and the corresponding eigenfunctions $\mathrm{F}_\nu^m(\tau)$ of the Dirichlet problem for the Legendre equation,

$$\partial_\tau[(1-\tau^2)\partial_\tau \mathrm{F}_\nu^m(\tau)] + [\nu(\nu+1) - m^2(1-\tau^2)^{-1}]\mathrm{F}_\nu^m(\tau) = 0.$$

Using the Poisson equation in hyperboloid coordinates one can obtain the equation

$$\partial_\sigma[(\sigma^2-1)\partial_\sigma\Phi_{1\nu}(\sigma)] + [-\nu(\nu+1) - m^2(\sigma^2-1)^{-1}]\Phi_{1\nu}(\sigma) = -Q_{1\nu}(\sigma),$$

where the quantities $Q_{1\nu}(\sigma)$ may be obtained from the expansion $Q_1a^2(\sigma^2-\tau^2) = \sum_\nu Q_{1\nu}(\sigma)\mathrm{F}_\nu^m(\tau)$. Assumed that $\Phi_{1\nu}(\sigma) = \bar{\Phi}_{1\nu}(\sigma)(\sigma^2-1)^{m/2}$, one can get the equation

$$(\sigma^2-1)\partial_\sigma^2\bar{\Phi}_{1\nu}(\sigma) + 2(m+1)\sigma\partial_\sigma\bar{\Phi}_{1\nu}(\sigma) + [m(m+1) - \nu(\nu+1)]\bar{\Phi}_{1\nu}(\sigma) = -\bar{Q}_{1\nu}(\sigma)$$

and the boundary condition at the symmetry axis,

$$\lim_{\sigma\to1}\{2(m+1)\partial_\sigma\bar{\Phi}_{1\nu}(\sigma) + [m(m+1) - \nu(\nu+1)]\bar{\Phi}_{1\nu}(\sigma) + \bar{Q}_{1\nu}(\sigma)\} = 0.$$

The calculations were carried out for the discharge gap width near 1 mm. It was obtained the appearance of pulse mode, with voltage increase and with constant voltage value. The characteristic form of the clouds of positive ions is shown in the Fig. 2.

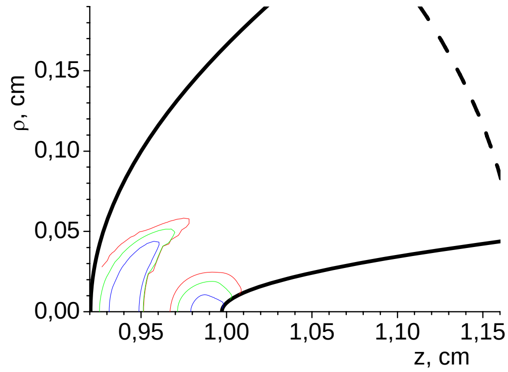

Fig. 2. The lines of the identical density 10^9, 10^{10}, 10^{11} cm^{-3} of positive ions at the time of the second pulse development

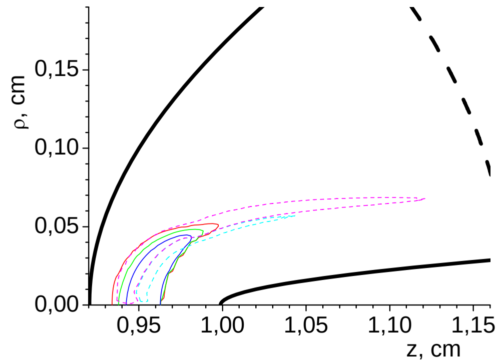

Fig. 3. The lines of the identical density 10^9, 10^{10}, 10^{11} cm^{-3} of positive ions (solid) and of the perturbations with the different signs (dashed) in some time after pulse

In some interval of the applied voltage values azimuthally homogeneous processes approach periodic pulsed mode, but amplitudes of perturbations of the azimuthal harmonic with $m = 1$ after each pulse get some factor, greater then unit, which means instability development. The characteristic feature of the harmonic is neighborhood of the regions of the positive ion density perturbations with the different signs, in each pulse (Fig. 3), but the perturbation with some sign in the half-space $\varphi \in (-\pi/2, \pi/2)$ is much greater than one with the opposite sign, and in the following pulses it is greater the perturbations with the sign opposite to one, which predominates in this half-space. Such sign altering by turn corresponds to divergence of the clouds of positive ions in the directions $\varphi = 0$ and $\varphi = \pi$. If the pulses similar to the considered ones take place at the time of streamer channel destruction after streamer bridging the gap not long before new streamer start then streamer, starting, has in front of itself the definite succession of positive clouds situated by turn on each side with respect to the symmetry axis. Namely, the nearest cloud is on the opposite side, the next one is on the same side as the streamer start point, the farther one is on the opposite side, and so on. The positively charged cathode-directed streamer has the property to pass over the positively charged regions, in connection with the field weakening between it and such region due to the opposite strength directions of their field. Such property with the definite disposition of the clouds and with high probability of each streamer start from the same point of anode (which is distinguished with field concentration) definitely determines the sinuous streamer trace.

The calculations of ionization development after application of voltage to the gap with small electron density show, at sufficiently large voltage, the greater rate of densities increase in the azimuthal harmonic with $m = 2$, comparatively with one in the main, axially symmetric distribution. Such pulse development corresponds to formation of the ramified streamer.

CONCLUSIONS

In the paper it is proposed hypothesis about the connection of the experimentally observed sinuous streamer trace with the instability of azimuthal harmonic of the pulsed positive corona. The linear stage of instability development is considered, the method of its investigation on the two-dimension mesh is described, and the results of calculations are presented, which show the possibility of the instability development. Also, there are carried out the calculations for higher harmonics corresponding to streamer bifurcation.

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РАЗВИТИЕ АЗИМУТАЛЬНО-НЕОДНОРОДНЫХ ПРОЦЕССОВ В КОРОННОМ РАЗРЯДЕ В АКСИАЛЬНО-СИММЕТРИЧНОМ ПРОМЕЖУТКЕ

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Выдвинута гипотеза о связи наблюдаемого в эксперименте извилистого следа стримера с неустойчивостью азимутальной гармоники импульсной положительной короны. Изложен метод исследования неустойчивости в линейном приближении на двумерной сетке и проведены расчеты, результаты которых свидетельствуют о наличии неустойчивости. Проведены расчеты для высших азимутальных гармоник, соответствующих ветвлению стримера.

РОЗВИТОК АЗИМУТАЛЬНО-НЕОДНОРІДНИХ ПРОЦЕСІВ У КОРОННОМУ РОЗРЯДІ В АКСІАЛЬНО-СИМЕТРИЧНОМУ ПРОМІЖКУ

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Висунуто гіпотезу про зв'язок, що спостерігався в експерименті, звивистого сліду стримера з нестійкістю азимутальної гармоніки імпульсної позитивної корони. Викладено метод дослідження нестійкості у лінійному наближенні на двовимірній мережі та проведено розрахунки, результати яких свідчать про наявність нестійкості. Проведено розрахунки для вищих азимутальних гармонік, що відповідають галуженню стримера.