AZIMUTHAL INSTABILITY OF THE PULSED POSITIVE GLOW CORONA AND SINUOUS STREAMER TRACE

O. Bolotov, V. Golota, B. Kadolin, V. Ostroushko, I. Pashchenko, L. Zavada

NSC “Kharkov Institute of Physics and Technology”, Kharkov, Ukraine

E-mail: ostroushko-v@kipt.kharkov.ua

The numerical simulations of positive corona at the constant voltage less than streamer mode threshold are carried out. The pulse mode based on photon generation and photo-ionization is obtained, and its simple analytical model is proposed. In addition to axially symmetrical process, it is studied the instability of the azimuthal harmonic, in the linear approximation, on the same two-dimensional mesh. It is noted the possible connection of the first harmonic instability with the sinuous streamer trace obtained in photo.

PACS: 52.80.Hc

INTRODUCTION

Even if electrode system and gas properties are axially symmetric the process development may break an axial-symmetry. For example, there may take place the flashes by turn in two near areas of the needle anode surface in positive corona [1].

The numerical simulations of axially symmetric processes may be carried out on two-dimension mesh. Three dimension simulations demand much greater computer power, and it is possible to simulate only comparatively simple systems now. But to reveal the instability of an axially symmetric process with respect to development of the azimuthally non-uniformity, it is not necessary to carry out three-dimension simulations. Assuming the non-uniformity small, one can make linearization of the nonlinear equations for change of the charged particle densities with respect to the non-uniformity. And using the independence of the different azimuthal harmonics in the linear problem, one can integrate with time the nonlinear equations for the axially symmetric process and the linear equations for one or several azimuthal harmonics, on the same two-dimension mesh.

Such approach was applied to ‘positive glow corona’ mode, which arises at voltage, greater than one sufficient for the self-consistent discharge operation, but less than one necessary for streamer formation. Azimuthal instability of such mode may lead to the sinuous streamer trace observed on the photo described below.

1. POSITIVE GLOW CORONA

The processes connected with the positive glow corona develop mainly near the needle anode. Positive glow corona accompanies with the pulses of total current and light intensity. In the paper [2], it is well explained the physical mechanism of the pulses and of the oscillations, from which the pulses develop. It is worthy to supplement the explanation with the simple model. Its analysis helps to find out the influence of the different factors on the development of oscillations.

For self-consistency, discharge needs in a source of electrons and in a mechanism of the source feeding with aid of the available electrons. In air discharge, the source may be ionization of oxygen molecules, and the photons necessary for it may be radiated from the exited states of nitrogen molecules. In the one-component gas, there are no states, which energy exceeds the ionization energy, but it is possible the associative ionization, which lies in the joining of the exited molecule with another one (not necessary exited) and the following formation of ion and free electron. The ionization energy of the joined molecule is usually less than the ionization energy of the single simple molecule. In the frames of classical ideas, this corresponds to the fact that a neutral molecule is or becomes dipole and attracts to ion. Although the mentioned three phenomena (excitation of molecules by electrons, photon radiation, and release of electrons through photo-ionization) suffice for the discharge self-consistency, the availability of impact ionization leads to considerable intensification of electron multiplication and to decrease of voltage necessary for such discharge.

If voltage value is greater than the self-consistent discharge threshold then occasional intensification of ionization leads to increase of positive ion density. Positive charge weakens the field near anode, and ionization weakens. Through such degenerative feedback the discharge can operate in stationary mode, although the lag of ion charge accumulation from intensive ionization and the lag of intensive ionization from field strengthening may promote oscillations with the characteristic time determined by electron drift to anode. However, the oscillations may be dumped with relaxation [3]. Excitation of oscillations may be promoted with the effect of field strengthening in the space slightly distant from anode by the positive charge disposed nearer to anode. The process may be described with the equations

$$\partial_t N_{pa} + \nu_{pa} N_{pa} = f_a N_{ea} = \partial_t N_{ea} + \nu_{ea} N_{ea} - \nu_{ec} N_{ec} ,$$

$$\partial_t N_{pc} + \nu_{pc} N_{pc} - \nu_{pa} N_{pa} = f_c N_{ec} = \partial_t N_{ec} + \nu_{ec} N_{ec} .$$

In them ∂_t is time derivative, the indexes e and p indicate electrons and positive ions, the indexes a and c refer to the space nearer to anode and the space slightly distant from anode, ν_{ea}, ν_{ec}, ν_{pa}, and ν_{pc} are the quantities reciprocal to the characteristic time of removing of relevant particles from relevant spaces, f_a and f_c are ionization frequencies., N_{ea}, N_{ec}, N_{pa}, and N_{pc} are densities. The frequencies f_a and f_c are assumed to be dependent on the charge densities,

$$f_a = f_a(N_{pa} - N_{ea}, N_{pc} - N_{ec}) ,$$

$$f_c = f_c(N_{pa} - N_{ea}, N_{pc} - N_{ec}) .$$

ISSN 1562-6016. ВАНТ. 2014. №6(94)

PROBLEMS OF ATOMIC SCIENCE AND TECHNOLOGY. 2014, №6. Series: Plasma Physics (20), p. 195-197.

Let us introduce the designations $f_a^{(0)}$ and $f_c^{(0)}$ for the stationary values of the functions $f_a(N_a, N_c)$ and $f_c(N_a, N_c)$, and the designations $f_{aa}^{(1)}$, $f_{ac}^{(1)}$, $f_{ca}^{(1)}$, and $f_{cc}^{(1)}$ for the values of the derivatives with respect to charge densities at the stationary values of the densities (the second index at the bottom indicates the space, with respect to the density in which the derivative is taken). It may be sought that inequalities $f_{aa}^{(1)} < 0$, $f_{ac}^{(1)} < 0$, $f_{ca}^{(1)} > 0$, and $f_{cc}^{(1)} < 0$ are held. They mean that positive charge weakens the field in the space of its disposition and in the space nearer to anode and it strengthens the field father from anode, with relevant consequences for ionization frequency. A non-stationary solution is searched in the linear approximation, $N = N_0 + N_1 \exp(\nu t)$, where the indexes 0 and 1 indicate a stationary value and a small perturbation, respectively, and other indexes are not written. With usual method, one can get the equations for the stationary values, the linear equations for the perturbations, and the conditions of their nonzero solution existence. In particular, there are held the equalities $f_c^{(0)} = \nu_{ec}$ and $C_0 N_{ea0} = \nu_{ec} N_{ec0}$, where $C_0 = \nu_{ea} - f_a^{(0)}$. Taking into account that ion velocity is much less than electron one, for the perturbation increment ν one gets

$$\nu^4 \approx -C_0\nu^3 - C_1\nu^2 - C_2\nu - C_3 ,$$

where

$$C_1 = N_{ea0}[C_0(f_{ca}^{(1)} - f_{cc}^{(1)}) - \nu_{ea} f_{aa}^{(1)}] ,$$

$$C_2 = N_{ea0}C_0(-f_{cc}^{(1)}C_0 - f_{ca}^{(1)} f_a^{(0)}) ,$$

$$C_3 = \nu_{ea} N_{ea0}^2 C_0(f_{aa}^{(1)} f_{cc}^{(1)} - f_{ca}^{(1)} f_{ac}^{(1)}) .$$

Supposing that ionization coefficient in the space a achieves the saturation, so that $f_{aa}^{(1)}$ and $f_{ac}^{(1)}$ are very small, in comparing with $f_{ca}^{(1)}$ and $f_{cc}^{(1)}$, one can obtain the relationship $\nu \approx -C_3 / C_2$ (for one very small increment) and the relationship

$$\nu^3 \approx -C_0[\nu^2 + N_{ea0}(f_{ca}^{(1)} - f_{cc}^{(1)})\nu +$$
$$+ N_{ea0}(-f_{cc}^{(1)}C_0 - f_{ca}^{(1)} f_a^{(0)})]$$

(for three other increments). If ionization takes place mainly in the space a, so that $C_0 << \nu_{ea} \approx f_a^{(0)}$, then for the mentioned three increments one gets $\nu^3 \approx C_0 N_{ea0} f_{ca}^{(1)} \nu_{ea}$. One of them is positive. It corresponds to monotonous instability. Two other increments are complex conjugated. They have negative real part, which means the dumped oscillations. In the case of small C_0, the very small increment mentioned above is also positive. It corresponds to the monotonous instability with very slow development.

2. RESULTS OF NUMERICAL SIMULATIONS

If one is interesting in common features of corona discharge then it is expedient to consider the space bounded by prolate ellipsoid of revolution and by electrodes, hyperboloids of revolution with the same focuses, and to use hyperboloidal coordinates. Potential in such space may be obtained with the expansion in terms of eigenfunctions of relevant problem for the coordinate, which is constant at hyperboloids. In the linear approximation, potential and densities of harmonic with the number m depend on polar coordinates (ρ, φ) near axis through the factor $\rho^m \cos(m\varphi)$. It is expedient to remove relevant factor in hyperboloidal coordinates and to write the equations for the coefficients at it.

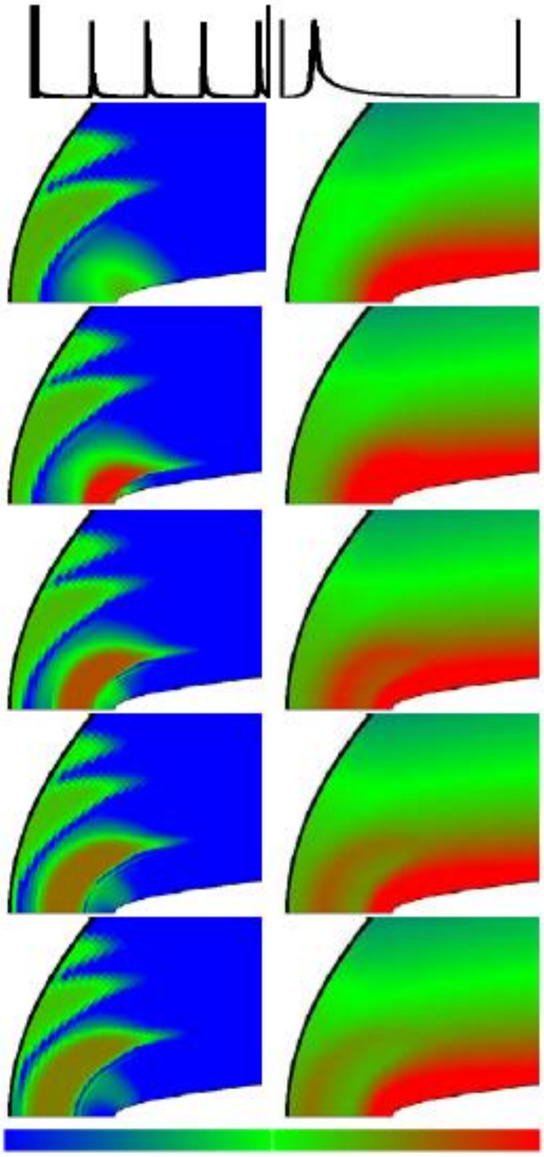

Fig. 1. Positive ion density and field strength with time step 50 ns; the quantities are logarithmically distinguished by color (range at the bottom) in intervals $10^{9}...10^{13}$ cm^{-3} and $10^4...10^5$ V/cm; relevant time dependence of total current (within 200 ns) is in right plot at the top; left plot includes 2 μs; anode and cathode are right and left hyperboloids

The simulations were carried out for the electrode spacing near 1 mm and constant voltage. The obtained pulse mode is approaching to the periodic one. In result of every pulse the perturbation amplitudes for the first ($m = 1$) azimuthal harmonics get some factor greater than unit, which means instability development. A typical look of the formed positive ion bunches is shown in the Fig. 1. Also, at successive pulses, the azimuthal harmonic of the charge in the half-space $\cos\varphi > 0$ obtains the different signs by turn, which means divergence of positive ion bunches in opposite directions.

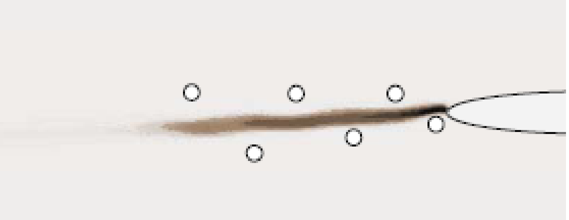

Fig. 2. Photo of streamers trace near anode with exposition 2 minutes; anode (oval) and a probable disposition of positive bunches just before streamer start (circles) are sketched

Formerly, it was obtained the photo (Fig. 2) of positive corona in the streamer mode with exposition, during which the streamers were formed hundreds of thousands times. According to the photo, every streamer has left approximately the same trace; its form near anode is sinuous. So, the streamer, as by inertia, continues to change the direction of its movement and tends to move not by the shortest way to cathode, but somewhat sideway, whereas at atmospheric pressure the usual mechanical inertia is dumped through collisions. To explain such streamer behavior, it may be supposed that before the start of every streamer, at the end of destruction of previous streamer channel, the field strength near anode increases up to the value sufficient for the pulsed positive glow corona mode. In connection with its azimuthal instability, there is the appointed succession of the positive bunches situated by turn near anode just before every streamer start. Namely, the nearest bunch and the streamer are opposite with respect to symmetry axis, and the next bunch is opposite to the previous one (as it is sketched in the Fig. 2). The field in the space between the formed cathode-directed positively charged streamer and any positive ion bunch is weakened through the opposite directions of their field strength. So, the streamer almost does not develop in the bunch direction and goes round bunch. Also, there is great probability of every streamer start from the determined space near anode, which is distinguished by local field enhancement. These three things (appointed disposition of bunches, trying of a streamer to go round bunch, and appointed space of streamer start) certainly determine the sinuous streamer trace.

CONCLUSIONS

In the work, the axially symmetric simulations of positive corona at the constant voltage less than the streamer mode threshold are carried out, and the linear stage of the azimuthal harmonic instability development is studied. The pulsed mode based on photon generation and photo-ionization is obtained, and the simple analytical model clarified its mechanism is proposed. It is pointed out the possible connection of the first harmonic instability with the sinuous streamers trace observed on photo.

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Article received 28.10.2014

АЗИМУТАЛЬНАЯ НЕУСТОЙЧИВОСТЬ ИМПУЛЬСНОЙ ПОЛОЖИТЕЛЬНОЙ КОРОНЫ И ИЗВИЛИСТЫЙ СЛЕД СТРИМЕРА

О. Болотов, В. Голота, Б. Кадолин, В. Остроушко, И. Пащенко, Л. Завада

Выполнено численное моделирование положительной короны при постоянном напряжении, меньшем, чем порог для стримерного режима. Получен импульсный режим, основанный на генерации фотонов и фотоионизации, и предложена его простая аналитическая модель. Кроме аксиально-симметричного процесса, исследуется неустойчивость азимутальных гармоник в линейном приближении на той же двумерной сетке. Указано на возможную связь неустойчивости первой гармоники с извилистым следом стримера, полученным на фото.

АЗИМУТАЛЬНА НЕСТІЙКІСТЬ ІМПУЛЬСНОЇ ПОЗИТИВНОЇ КОРОНИ ТА ЗВИВИСТИЙ СЛІД СТРИМЕРА

О. Болотов, В. Голота, Б. Кадолін, В. Остроушко, І. Пащенко, Л. Завада

Виконано числове моделювання позитивної корони при постійній напрузі, меншій від порогу для стримерного режиму. Отримано імпульсний режим, який ґрунтується на генерації фотонів та фотоіонізації, і запропоновано його просту аналітичну модель. Крім аксіально-симетричного процесу, досліджується нестійкість азимутальних гармонік у лінійному наближенні на тій же двовимірній мережі. Вказано на можливий зв’язок нестійкості першої гармоніки зі звивистим слідом стримера, отриманим на фото.