SEVERAL PEAKS OF TOTAL CURRENT IN TRICHEL PULSE

O. Bolotov, V. Golota, B. Kadolin, S. Mankovskyi, V. Ostroushko, I. Pashchenko, G. Taran, L. Zavada

NSC "Kharkov Institute of Physics and Technology" Kharkov, Ukraine

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

The numerical simulations of negative corona at constant voltage in Trichel pulse mode are carried out in assumptions of presence and absence of photoemission from cathode. In absence of photoemission two peaks of total current or the step before the main peak were obtained for very small values of ion-electron emission coefficient. In presence of photoemission there were observed several maximums, connected with instability development of the process based on radiation of photons, photoemission, and avalanche multiplication.

PACS: 52.80.Hc

INTRODUCTION

In some experimental conditions, a total current time dependence of one Trichel pulse in negative corona has several maximums [1]. Formerly, the numerical simulations were carried out for one-dimensional particle distribution with the field corresponding to disks [2, 3], and for three-dimensional axially symmetric model [4]. There were accounted ion-electron emission (in [2-4]) and photoemission (in [2]). Two peaks were obtained in [2] and [3]. In [2], the first peak is accompanied with intensive photoemission, and the second with ion-electron emission. In [3], at cathode, the first peak corresponds to displacement current maximum and is connected with ionization wave, and the second peak corresponds to conduction current maximum. In [4], total current has one maximum, although there is observed the propagation of ionization wave in the space near cathode. The time between peaks obtained in simulations was too large, in comparing with one obtained in the experiment [1].

The explanation proposed in [1], in which decisive role belongs to ionization wave, does not indicate clearly the causes of total current decrease between its maximums. The results of numerical simulations suggest two possible causes of this decrease. One cause is connected with decay of fast ionization wave. A new increase of total current after wave decay may be connected with comparatively slow increase of ion current at cathode or with field strengthening and ionization rate increase near transverse ends of plasma region in consequence of transverse expansion of ionization wave. Another cause of total current oscillations is connected with instability of the process based on radiation of photons, photoemission, and impact ionization.

1. IONIZATION WAVE AND ION CURRENT

In simulations carried out without photoemission account, the pulses with two peaks of total current, and, also, the pulses with a step before single peak were obtained in two different assumptions about ion mobility dependence on electric field strength. Namely, the strength increase may cause increase or decrease of the mobility. Two peaks were obtained with the decrease and the step with the increase. The current increase before the first peak or the step was connected with development of ionization wave. The second and single peaks were connected with intensive going out of ions to cathode.

Near-cathode ionization wave is somewhat similar to streamer, but neighborhood of needle cathode leads to some differences of the wave from cathode directed streamer, developing in the mid-space far from the needle. Great field strength near head of the streamer is caused by great charge of the head, and farther from the head the strength is less. Like the streamer, the wave is accompanied with forming of plasma region and increase of field strength near some side of the plasma region up to the values characteristic for streamer. But field strength increases in the whole space between the plasma region and cathode, and strength is greater in the space nearer to cathode. After formation, the plasma region is expanding to cathode, and approximately the same voltage drop between the plasma region and cathode is becoming correspondent to the decreasing distance. So, in the space between the plasma region and cathode, the field strength and ionization coefficient increase, and to do the same number of ionization acts an electron needs the shorter drift path. Finish of such drift with ionizations corresponds to entering of the electron into the end of plasma region nearer to cathode with plasma forming in this place. In the stronger field such drift is finished at the nearer distance from cathode. After the strength increase up to the values, at which ionization coefficient depends on the strength faintly, the development of the described ionization wave is considerably slowing down, and displacement current considerably decreases, leading to some decrease of total current.

As field near cathode is not uniform, in the different areas over the cathode surface the wave develops with different rates. The developing is slower in the weaker field farther in the direction transverse to the field strength. So, the process gets the form of transverse ionization wave expansion after considerable slowing down of its expansion along the field strength. The written above may be illustrated by Fig. 1, where electron distribution near cathode is shown towards the ends of the longitudinal and transverse ionization wave expansions. It was obtained in assumption of ion mobility decrease with field strength increase.

The second peak may arise in connection with going out of positive ions to cathode. Development of avalanches, starting by electrons from cathode, yields steep ion density increase with the distance from cathode. Going out of such distribution to cathode leads to increase of conduction current at cathode, which is the main part of the total current at this time. After the going out of the main part of the formed positive ions, the total current decreases.

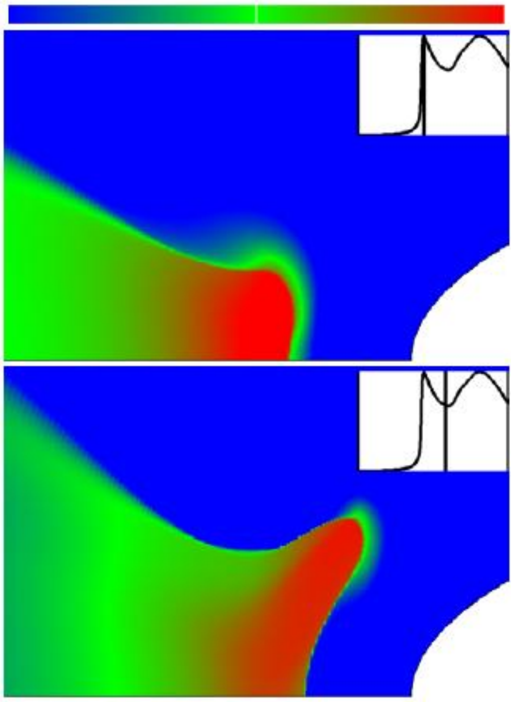

Fig. 1. Electron density near cathode towards the ends of longitudinal and transverse ionization wave expansions (time difference 28 ns) in assumption of ion mobility decrease with field strength increase; densities are logarithmically distinguished by color (range at the top) in interval $10^{9}\ldots10^{15}$ cm^{-3}; in the total current time dependence in corner the instant is marked

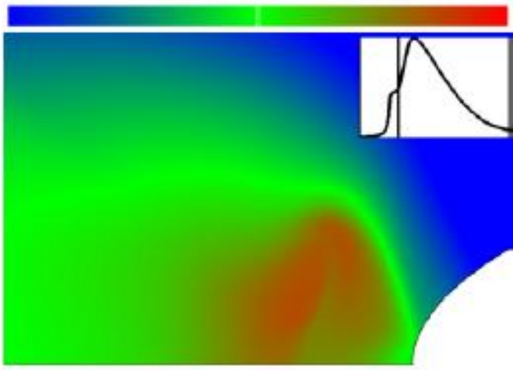

Fig. 2. Density of positive ions at the beginning of going out of their main part to cathode in assumption of ion mobility increase with field strength increase; densities are logarithmically distinguished by color in interval $10^{9}\ldots10^{15}$ cm^{-3}

If ion mobility in strong field is sufficiently large then considerable increase of conduction current at cathode may take place at the time of considerable slowing down of the ionization wave longitudinal expansion, and instead of minimum between two peaks of total current it is formed somewhat similar to the step before the main peak. Such case is illustrated in Fig. 2 by positive ion distribution at the beginning of going out of their main part to cathode (and total current step formation). It was obtained in assumption of ion mobility increase with field strength increase.

The simulations yielded two peaks of total current only for the values of ion-electron emission coefficient considerably less than the usually taken values $10^{-4}\ldots10^{-3}$. On the value of the coefficient, it depends how far from cathode the considerable slowing down of ionization wave takes place. For the larger coefficient, it takes place nearer to cathode, in connection with greater electron flow from cathode. To come to cathode from there, the ions need less time, and two peaks may be transformed to single peak, as it took place in simulations [4].

2. OSCILLATIONS WITH PHOTOEMISSION

If photoemission is considerable then even a few peaks of total current may be formed, in connection with two effects: (1) enlarging of ionization rate in the part of space and photon radiation from there when electric field strength there increases, (2) increase of the strength in front of bunch of electrons, which have been knocked out from cathode by photons and are moving to anode. Oscillations may be found out even only on the base of photon radiation from discharge space and photoemission from cathode. Let us consider the model, in which only two spaces are accounted: the space c near cathode, and the space b somewhat farther from cathode. The process may be described with the equations

$$\partial_t N_b = \nu_c N_c - \nu_b N_b ,$$

$$\partial_t N_c = f_c(N_c, N_b) N_c + f_b(N_c, N_b) N_b - \nu_c N_c .$$

Here ∂_t is time derivative, the indexes c and b indicate the spaces, ν_x is reciprocal to the characteristic time of electron removing from the space x, where x stands for c or b, N_x is electron density, f_x is photon generation frequency. Let us put $N_x = N_{x0} + N_{x1}\exp(\nu t)$, where the indexes 0 and 1 indicate a stationary value and a small perturbation. Let us use the designations $f_x^{(0)}$, $f_{xc}^{(1)}$, $f_{xb}^{(1)}$, respectively, for the values of $f_x(N_c, N_b)$, $(\partial/\partial N_c) f_x(N_c, N_b)$, $(\partial/\partial N_b) f_x(N_c, N_b)$ at { $N_c = N_{c0}$, $N_b = N_{b0}$ }. Let us put $f_x^{(1)} = f_x^{(0)} + N_{c0} f_{cx}^{(1)} + N_{b0} f_{bx}^{(1)}$, $A = \nu_b + \nu_c - f_c^{(1)}$, $B = (\nu_c - f_c^{(1)} - \nu_b)^2 + 4\nu_c f_b^{(1)}$. For stationary values, one gets the equations $\nu_c N_{c0} = \nu_b N_{b0}$ and $(\nu_c - f_c^{(0)}) N_{c0} = f_b^{(0)} N_{b0}$, and the condition $\nu_c f_b^{(0)} + \nu_b f_c^{(0)} = \nu_c \nu_b$ of their nonzero solution existence. For linear perturbations, one gets the equations $(\nu + \nu_c - f_c^{(1)}) N_{c1} = f_b^{(1)} N_{b1}$ and $(\nu + \nu_b) N_{b1} = \nu_c N_{c1}$, and the condition $(2\nu + A)^2 = B$. The inequality $A < 0$ means instability, and $B < 0$ means oscillations. It is assumed that $f_{cb}^{(1)} < 0$, $f_{bb}^{(1)} < 0$, $f_{cc}^{(1)} < 0$, and $f_{bc}^{(1)} > 0$, according to influence of the negative charge disposition on the field in relevant spaces. For instability, the inequality $f_c^{(0)} + N_{b0} f_{bc}^{(1)} > \nu_b + \nu_c - N_{c0} f_{cc}^{(1)}$ should be held. Oscillations correspond to the inequality

$$4\nu_c(-N_{c0} f_{cb}^{(1)} - N_{b0} f_{bb}^{(1)}) > 4\nu_c f_b^{(0)} +$$
$$+(f_c^{(0)} + N_{b0} f_{bc}^{(1)} + \nu_b - \nu_c + N_{c0} f_{cc}^{(1)})^2 .$$

In particular, if the value of $f_{bc}^{(1)}$ is sufficiently large then the process is unstable. And, for the given $f_{bc}^{(1)}$, if the values of $|f_{cb}^{(1)}|$ and $|f_{bb}^{(1)}|$ are sufficiently large then the instability is oscillatory.

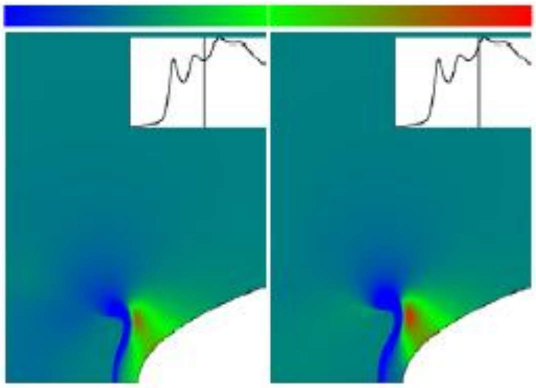

Fig. 3. The rates of the field strength changes separated with time 0.5 ns; the rates are linearly distinguished by color from -5×10^{13} V·cm^{-1}·s^{-1} to +15×10^{13} V·cm^{-1}·s^{-1}

With impact ionization, the instability may be considerably enhanced due to electron multiplication. Intervals between maximums correspond to the time of electron drift from cathode to the space of intensive photon radiation near the plasma region. This time is considerably less than the time of positive ion drift from plasma region to cathode, and it corresponds to the time between peaks of total current obtained in experiment [1]. In Fig.3, the rates of field strength change are shown for two instants, which belong to time intervals of total current slow change and rapid increase. Time derivative of field strength in the space near the transverse ends of plasma region is positive, which is partially connected with ionization wave expansion in this direction. But from time to time the rate of strength change there increases additionally, due to the next approach of the increased number of electrons, which were obtained as consequence of the previous approach, through the increase of photon radiation from the space, electron emission from cathode, and electron multiplication in avalanches. The field near the plasma region is not so strong as one near the cathode surface, the photon generation frequency there is less, but sensitivity of the frequency to the field strength value is higher, and the greater (through multiplication) number of electrons compensates the smaller frequency, so that comparatively small oscillations of the field strength near the plasma region yield considerable oscillations of total current.

CONCLUSIONS

In Trichel pulse mode of negative corona, during transition from simple avalanche multiplication to ionization wave set up, the total current usually changes monotonously without any temporary decreases. Several total current maximums with time intervals of order of nanosecond obtained in experiments, probably, are connected with instability of the process based on the photon radiation from discharge space, photoemission from cathode, and electron multiplication due to impact ionization. The first maximum is connected with considerable slowing down of longitudinal expansion of ionization wave.

REFERENCES

1. M. Černak, T. Hosokawa, S. Kobayashi, T. Kaneda. Streamer mechanism for negative corona current pulses // *Journal of Applied Physics.* 1998, v. 83, № 11, p. 5678-5690.
2. R. Morrow. Theory of stepped pulses in negative corona discharges // *Physical Review A*. 1985, v. 32, № 6, p. 3821-3824.
3. A.P. Napartovich, Yu.S. Akishev, A.A. Deryugin, I.V. Kochetov, M.V. Pan’kin, N.I. Trushkin. A numerical simulations of Trichel pulse formation in a negative corona // *Journal of Physics D: Applied Physics*. 1997, v. 30, p. 2726-2736.
4. Yu.S. Akishev, I.V. Kochetov, A.I. Loboiko, A.P. Napartovich. Numerical simulations of Trichel pulses in a negative corona in air // *Plasma Physics Reports*. 2002, v. 28, № 12, p .1049-1059.

Article received 20.10.2014

НЕСКОЛЬКО ПИКОВ ПОЛНОГО ТОКА В ИМПУЛЬСЕ ТРИЧЕЛА

О. Болотов, В. Голота, Б. Кадолин, С. Маньковский, В. Остроушко, И. Пащенко, Г. Таран, Л. Завада

Выполнено численное моделирование отрицательной короны при постоянном приложенном напряжении в режиме импульсов Тричела в предположениях наличия и отсутствия фотоэмиссии с катода. При отсутствии фотоэмиссии два пика полного тока или ступенька перед основным пиком были получены при очень малых значениях коэффициента ионно-электронной эмиссии. При наличии фотоэмиссии наблюдалось несколько максимумов, связанных с развитием неустойчивости процесса, основанного на излучении фотонов, фотоэмиссии и размножении лавин.

КІЛЬКА ПІКІВ ПОВНОГО СТРУМУ В ІМПУЛЬСІ ТРИЧЕЛА

О. Болотов, В. Голота, Б. Кадолін, С. Маньковський, В. Остроушко, І. Пащенко, Г. Таран, Л. Завада

Виконано числове моделювання негативної корони при постійній докладеній напрузі в режимі імпульсів Тричела в припущеннях наявності та відсутності фотоемісії з катода. За відсутності фотоемісії два піки повного струму або сходинка перед основним піком були отримані при дуже малих значеннях коефіцієнта іонно-електронної емісії. За наявності фотоемісії спостерігалося кілька максимумів, пов’язаних з розвитком нестійкості процесу, який ґрунтується на випромінюванні фотонів, фотоемісії та розмноженні лавин.