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DRIFT OF ELECTRONS IN GAS IN SPATIALLY INHOMOGENEOUS PERIODIC ELECTRIC FIELD

The paper presents the results of calculations of the characteristics of the electron drift in a constant periodic spatially inhomogeneous electric field. It has been shown that, in typical experiments with a gas plasma at a reduced gas pressure, the influence of field inhomogeneities on the drift velocity and the average energy of the electrons is negligible. But the excitation and ionization intensities and the spatial distribution of plasma are strongly dependent both on the value of inhomogeneity (dispersion) and the nature of the changes in the field. It has been shown that an inhomogeneity of the electric field in the positive column of a gas discharge forces the electron energy distribution function to be the Maxwell one.

Keywords: drift of electrons, spatially inhomogeneous periodic electric field, gas plasma.

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When considering the various tasks associated with the drift of electrons in a gas-discharge plasma, it is often assumed that the rate of a drift and all its characteristics at each point of the space (average energy, diffusion coefficients, ionization and energy Townsend coefficients) depend only on the electric field and the gas density (or on the reduced field E/N) at this point. However, many phenomena in plasma discharge physics are caused by the non-locality effect, when the characteristics of the electronic components at a given point depend on the parameters of an electron gas at other points [1–4].

This paper presents the results of calculations of the characteristics of the electron drift in the periodic field and the analysis of the dependences of drift characteristics on the magnitude of spatial fluctuations of the field. The electron drifts in the electric field

$$E(x) = E_0\{x/L\}^n/(n+1), \tag{1}$$

where L – period, $\{x\}$ – the fractional part of x, $\{x\} = x - [x]$, and $[x]$ – the integer part of x, or in a sinusoidal one

$$E(x) = E_0\{1 + \alpha \sin(x/L)\}. \tag{2}$$

For the drift of electrons in neon, the detailed tabulation of different drift characteristics was carried out in [3]. For the values of a reduced electric field $E/N > 0.1Td$, the average kinetic energy of an electron is much greater than the energy (temperature) of atoms. At $E/N < 2Td$, the electron drift in neon is determined only by the elastic collisions with atoms [2].

During the drift, the electrons acquire an energy by the Joule heating $Q_{EW} = eEW$, where e – the electron charge, E – electric field, W – the drift velocity. This energy is lost in elastic collisions with atoms and is spent on the excitation of atomic levels and ionization: $Q_{EW} = Q_{\rm ea} + Q_{\rm ex} + Q_{\rm ion}$.

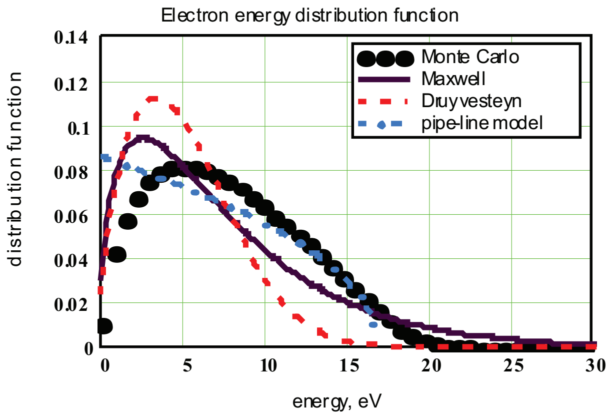

Fig. 1. Electron energy distribution function (EEDF) at the drift in a uniform electric field ($E/N = 13.5$ Td, neon). Bullets – the results of Monte Carlo calculations. For comparison, the Maxwell EEDF (solid curve), Druyvesteyn EEDF (dashed curve), and pipe-line distribution (dot-dashed curve) are also given

The electron energy distribution function (EEDF) and the integral characteristics of the electron drift were calculated by the Monte Carlo method [3, 4]. In these simulations, the following conditions were used. For the process of electron drift in the positive column, we can assume that the total number of births and deaths of electrons are equal. Then the death of electrons on the walls can be taken into account by introducing a rule into the algorithm that, for each act of ionization, one electron is removed from the whole ensemble. The most logical for the problem of the electron drift in a positive column is the assumption that the most energetic electrons can leave the ensemble. The average energy of electrons that leave the system can provide a good estimation of the potential of the wall. Thus, the wall potential is determined from the condition that the number of ionization events is equal to that of particles' escapes from the system.

Characteristics of the field and the electron drift in neon at a temperature of 298 K in the average reduced electric field $E/N = 10Td$

No.	$\frac{eE_0}{\lvert e\rvert}$, V/cm	n	δ^2	W, cm/s	$\langle\varepsilon\rangle$, eV	$Q_{\rm ex}$, eV	$\frac{Q_{\rm ion}}{Q_{EW}}$
1	4	0	0	19.7	7.75	79.3	1.7
2	4	1	1/3	19.4	7.54	78.6	2.8
3	–4	1	1/3	–19.3	7.58	79.4	2.4
4	4	–	1/2	18.8	7.29	78.2	3.4
5	4	2	9/5	18.7	7.21	77.9	4.3
6	–4	2	9/5	–18.8	7.31	79.1	3.5
7	4	3	16/7	18.3	6.94	77.1	5.8
8	–4	3	16/7	–18.4	7.08	79.2	4.3
9	4	4	25/9	17.9	6.71	76.6	6.9
10	–4	4	25/9	–17.8	6.89	78.9	5.0
11	4	5	36/11	17.5	6.53	76.3	7.8
12	–4	5	36/11	–17.6	6.73	78.4	6.0

For comparison, we also present the distributions of Maxwell, Druyvesteyn, and that of the pipe-line model [1]. The pipe-line model is a model, in which the formation of the EEDF is determined by the Joule heating and non-elastic collisions, whereas the energy loss of electrons at elastic collisions with atoms is assumed to be negligible [1, 2].

In Table, we show the following results of Monte Carlo simulations [1] of the electron drift characteristics in neon at a temperature of 298 K, given the average electric field $E/N = 10Td$: the drift velocity W, average energy $\langle\varepsilon\rangle$, percentage of the energy input that went to the excitation $Q_{\rm ex}/Q_{EW}$ and the ionization $Q_{\rm ion}/Q_{EW}$. As a measure of the variance heterogeneity, we give δ^2 normalized to the mean field:

$$\delta^2 = [\langle E^2(x)\rangle - \langle E(x)\rangle^2]/\langle E^2(x)\rangle. \qquad (3)$$

Calculations 1–12 in Table are ordered with increasing the spatial heterogeneity of the periodic field. All calculations, except number 4, were performed for the field inhomogeneity of the power nature (1). In number 4, the field was a sinusoidal perturbation (2) with the amplitude equal to the mean field: $\alpha = 1$. A wide variety of drift characteristics was calculated. The drift is along the x-axis, i.e., the drift velocity is positive in a negative average field. The Townsend ionization coefficient normalized to the ionization potential corresponds to the percentage of ionization losses $Q_{\rm ion}/Q_{EW}$ in the energy input $Q_{\rm ex}/Q_{EW}$.

The data in Table give a quite complete picture of the quality characteristics of the electron drift in an electric field.

Figure 1 shows the electron kinetic energy distribution for calculation 1 (uniform field). For the purposes of comparison, the Maxwell and Druyvesteyn distributions with the same average energy of electrons and the electron distribution function according to the pipe-line model are also shown. It is ev-

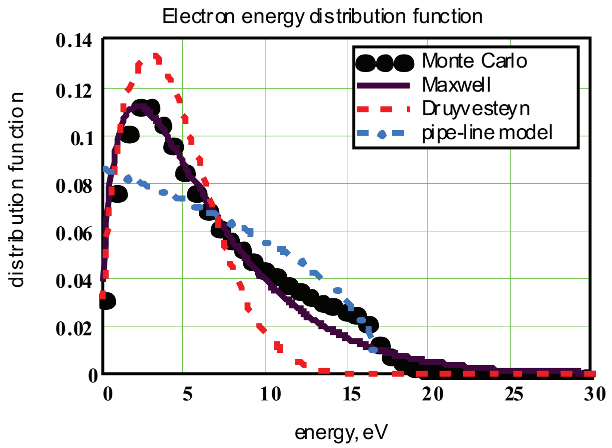

Fig. 2. Distribution function of the electron energy at the drift in a uniform electric field (E/N = 13.5 Td, neon). Bullets – the results of Monte Carlo calculations. For comparison, the Maxwell EEDF (solid curve), Druyvesteyn EEDF (dashed curve), and pipe-line distribution (dot-dashed curve) are also given

ident that neither Maxwell nor Druyvesteyn distribution do not provide, however, even a qualitative agreement with the results of Monte Carlo calculations. Perhaps, the best match between the calculations and the theory is achieved, when a pipeline approach is applied. Nevertheless, the scope of its applicability is limited. It should be noted that, besides the existence of a well-known strong influence of inelastic processes of excitation and ionization on the tail of the distribution function, there is a very significant effect of inelastic processes on the electron distribution function in the area of subthermal energies. The distribution of electrons in the area $\varepsilon \ll T_e$ differs essentially from the Maxwell and Druyvesteyn distributions due to a significantly high energy of an electron at the moment of its appearance after the ionization. At the excitation of an electron, the energy is $\langle \varepsilon - E \rangle/2 = 2 \div 3$ eV, while $\langle \varepsilon - I \rangle/2 = 2 \div 3$ eV at the ionization. Figure 2 shows the calculation results from Table: the drift occurs in the direction of increasing the field modulus at its high heterogeneity ($n = 5$). As Fig. 1, Table shows the Maxwell and Druyvesteyn distributions with the same average energy of electrons and the electron distribution function of the pipe-line model. It may be seen that the effect of heterogeneity in fact leads to the maxwellization of the distribution of electron energies. Figure 3 shows the re-

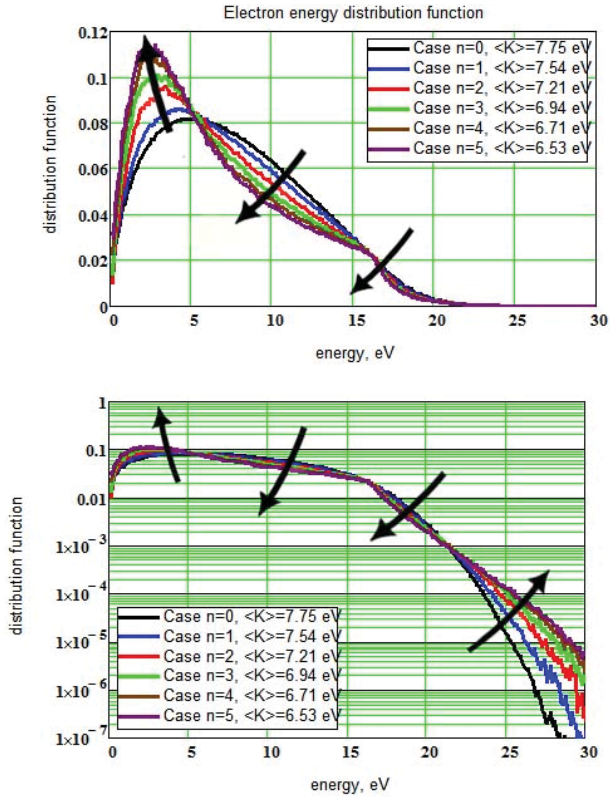

Fig. 3. Electron energy distribution in the drift in the periodic electric field (E/N = 10 Td, neon, the field period is equal to 4 cm, field intensity – 4 V/cm). Different curves correspond to different values of the exponent field inhomogeneity. The arrows indicate the direction of changes with the increase of fluctuations of the field

sults of calculations, in which the drift is in the direction of increasing the field modulus at different values of the exponent heterogeneity. This figure shows the effect of the degree of inhomogeneity of the field on the EEDF.

The electron energy distribution functions are compared with the Maxwell and Druyvesteyn distributions and with the unlimited drain model (pipe-line model) [1]. From the analysis of the results of calculations, we can state that even the large spatial fluctuations of the field do not lead to a large change in the average characteristics of the drift, namely, the drift velocity and the average energy of electrons; an increase in the field dispersion has the largest effect on the rate of ionization: there is a significant increase in the ionization rate and the proportion of the energy used for the ionization; the spatial inhomogeneity of the field can lead to the Maxwell EEDF in a glow Townsend discharge, which is the subject of a well-known and much-discussed Langmuir paradox [1].

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ДРЕЙФ ЕЛЕКТРОНІВ
У ГАЗІ В ПРОСТОРОВО НЕОДНОРІДНОМУ
ПЕРІОДИЧНОМУ ЕЛЕКТРИЧНОМУ ПОЛІ

Р е з ю м е

У роботі наведено результати розрахунків характеристик дрейфу електронів в постійному просторово неоднорідному періодичному електричному полі. Показано, що в типових умовах експериментів з газорозрядною плазмою при зниженому тиску газу вплив неоднорідностей поля на швидкість дрейфу і середню енергію електронів незначний. Але інтенсивності процесів збудження, іонізації, просторовий розподіл плазми сильно залежать як від величини неоднорідностей (дисперсії), так і від характеру зміни поля. Показано, що неоднорідність електричного поля в позитивному стовпі газового розряду приводить до максвеллізації функції розподілу електронів за енергією.