Diffuse, constricted-stratified and constricted modes of a DC discharge in argon. Simulation of transitions between these modes

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Abstract. This paper presents the results of theoretical studies of high-pressure (~10’s and 100s of Torr) dc discharges in argon. The diffuse, constricted-stratified, and constricted discharge modes are studied using a developed model. Two transitions were studied. One of them is transition from the constricted-stratified mode to the constricted mode. This transition occurs smoothly, without any jumps of plasma parameters. The other is a hysteresis transition between the diffuse and the constructed-stratified mode. It occurs by a jump and is accompanied by a several orders of magnitude increase in the electron density at the discharge axis and an appearance of moving striations.

1. Introduction
The phenomenon of the constriction of a direct current discharge in noble gases at the elevated gas pressures (tens and hundreds Torr) is well known in the physics of gas-discharge plasma. At attainment of a critical current the discharge structure and plasma parameters are changed abruptly and the discharge is compressed in a narrow bright filament. The current-voltage characteristic of the discharge is bi-stable. A transition from the diffuse to the constricted mode occurs by a jump and is accompanied by a several orders of magnitude increase in the electron density at the axis of the discharge tube. In the course of this transition, all the discharge parameters (the electric field, the plasma density, etc.) change abruptly. In passing back from the constriction to the diffuse mode, a hysteresis phenomenon is observed; i.e., a transition from the diffuse to the constricted-stratified mode (as the discharge current is increased) and the reverse transition (as the current is decreased) occur at different values of the discharge current. No striations were observed in the diffuse form of the discharge, the positive column is uniform along the tube axis. In wide range of discharge currents (~20-200 mA) constriction of the discharge is accompanied by the appearance of moving striations, which lead to modulation of plasma glowing regions. The shape of modulation is changed and its amplitude is decreased with current. Pulsation frequency comes down with current and the pulsation shape is changed from sinusoidal to substantially non-sinusoidal. This mode is distinct from purely constricted mode and it is necessary to consider the appearance of the striations (periodic fluctuations of plasma parameters). The constricted-stratified mode differs very much from purely stratified mode. For example, in the stratified mode in the region of high concentration of electrons, their concentration is smoothly distributed over the cross section of the discharge tube, while in the constricted-stratified mode it is concentrated in a narrow region near the discharge axis.
The processes leading to the constriction [1,2,3] and bringing the system out of the constricted [4] mode were studied in theoretical and experimental investigations of constricted discharges in noble gases. But to the best of our knowledge, until now, there were no publications in which the constricted-stratified mode was simulated self-consistently. In [5] there is only an experimental diagram where one can see a transition mode (constricted-stratified) between diffuse and constricted modes.

As mentioned above the constriction of the discharge is accompanied by the appearance of moving striations. The developed theoretical model of a dc discharge in all these modes has allowed us for the first time, to our knowledge, to obtain periodic fluctuations of plasma parameters for the constricted-stratified mode without any artificial assumptions.

In [4] the phenomenon of hysteresis transition was studied. The time dynamics was not studied in this article. The numerical model, that was used, allowed to study the basic processes leading to the discharge constriction and bringing the system out of the constricted mode. In the equation for high-energy part of electron energy distribution function (EEDF) was used the value of the electron temperature, which was found from local approximation instead of the equation for the electron temperature. It also suppresses the time fluctuations. Solving of full equations set (without using any time approximations), leads to appearance of the fluctuations of plasma parameters, which structure resemble striations. The temporal distribution of the distributions of charged particles and excited atoms correlate with the distribution of radiation intensity [2].

In this article, the simulation results for diffuse, constricted-stratified and constricted modes and transitions between these modes are presented.

2. Model
In this work, we simulate the diffuse, constricted-stratified and constricted discharge modes and describe numerically the hysteresis effect at the direct (with increasing discharge current) and reverse (with decreasing current) transitions between diffuse and constricted-stratified modes. A one-dimensional (radial) self-consistent model is developed that involves, as in [4], the continuity equations for electrons, ions (Ar⁺ and Ar₂⁺), and excited atoms (metastable and resonant), the conservation equation for electron energy; the heat conduction equation for the neutral gas; and Poisson's equation for the radial electric field. The processes included in the model are listed in table 1. At first, similar to [1], we solved a Boltzmann equation with account of electron-electron collisions in the local approximation. However, the determination of the excitation rate constants and the coefficients of direct and step ionization from the local EEDF calculated with account of electron-electron collisions did not allowed us to describe the hysteresis transition from the constricted-stratified to the diffuse mode. Therefore, the model was modified to account for the non-local character of the formation of the EEDF by introducing a two-temperature distribution function [4].

Table 1. List of reactions.

| Reaction Type          | Reaction                                      | Calculation k (cm³/s) using Cross sections [6] |
|------------------------|-----------------------------------------------|-----------------------------------------------|
| 1. Excitation          | Ar + e → Ar⁺ + e                              | k=1.8·10⁻₃¹, (300/T)³/₄ (cm⁶/s) [7] |
| 2. Ionization          | Ar⁺ + e → Ar⁺⁺ + e + e                        | EEDF for                                      |
| 3. Step ionization     | Ar⁺⁺ + e → Ar⁺⁺⁺ + e + e                      | k=4·10⁻⁵·T_e⁻⁰.⁶³ (cm³/s) [7] |
| 4. Conversion          | Ar⁺⁺ + Ar + Ar → Ar⁺⁺⁺ + Ar                   | k=5.7·10⁻⁷ (cm³/s) [8]                        |
| 5. Dissociative recombination | Ar⁺⁺⁺ + e → Ar⁺⁺ + Ar                        | k=5.1·10⁻⁹/(T[K])¹/₃ (cm⁶/s) [9] |
| 6. Electron impact dissociation | Ar⁺⁺⁺ + e → Ar⁺⁺ + Ar⁺ + e                    | k≈ θ·A (s⁻¹) [4]                             |
| 7. Three-body recombination | Ar⁺⁺ + e + e → Ar⁺⁺⁺ + e                      | k≈10⁻⁷ (cm³/s) [4]                          |
| 8. Radiative decay     | Ar⁺⁺ + e → Ar⁺⁺⁺ + e + e                      | EEDF for                                      |
| 9. States mixing       | Ar⁺⁺⁺ + e → Ar⁺⁺⁺ + e + e                     | EEDF for                                      |
As it appears in our model calculations, a transition from the constricted to the diffuse mode can be regarded as a demonstration of the non-local character of the formation of the high energy part of the EEDF: the diffusion of high-energy electrons (capable of producing gas ionization) from the central (constricted) region toward the periphery. The non-local formation of the distribution function is described by a non-local kinetic equation accounting for electron-electron collisions and electron radial transport. The effect of the non-local formation of the EEDF is taken into account by introducing the effective temperature $T^*$ of the high-energy part of the EEDF and solving the equation for the radial profile of $T^*(r)$. It should be noted that the usage only of the non-local equation for mean electron energy $3/2 \cdot T_e$ does not allow to obtain and to describe the constricted-stratified mode and transition to the diffuse mode [4]. The approach with two electron temperatures $T_e(r)$ and $T^*(r)$ allows one to take into account approximately the non-local character of the EEDF without substantial consumption of computer resources. This non-local model makes it possible to numerically simulate the hysteresis transition between the diffuse and constricted-stratified modes, which is impossible in our calculations using the local approximation approach [4].

3. Results

As mentioned above, at wide range of gas pressures direct current discharge can exist in three modes: diffuse, constricted and transition region between them, which is constricted-stratified mode. At first, let’s consider diffuse and constricted modes of discharge. We carried out the systematic calculations of these modes. Figure 1 shows the radial profiles of the electron concentration in the diffuse (for a discharge current of 10 mA) and constricted (for a discharge current of 180 mA) modes of a dc discharge in argon at experimental conditions [2]: tube radius $R=1.5$ cm, a pressure of 40 Torr. In the diffuse mode, the radial profile of the electron density is smooth. In this mode, the diffusive losses prevail and the radial profile of the ionization rate is determined by (E/N profiles) non-uniform gas heating. In the constricted mode, unlike the diffuse mode, the plasma electrons are mainly concentrated in a narrow central region. The discharge constriction manifests itself in a sharp decrease in the diameter of the current channel (which is characterized by the high conductivity and the high electron density $n_e^0$) and a sharp increase in the degree of ionization (up to $n_e/N_e^0 \sim 10^{-3} - 10^{-4}$).

Between these two modes there is a wide region of the constricted-stratified mode. Transition from the diffuse to constricted mode, without passing the constricted-stratified mode at current increase, can exist only under high pressures ($P \cdot R \gtrsim 3$ atm·cm [10]). That’s why the hysteresis transitions, which are observed in various experiments [2,3,10], are the transitions between diffuse and constricted-stratified modes. Calculated electric field $E$ in the constricted-stratified mode must be averaged through the regions with high and low electric field to compare with experimental field $E$, which is usually measured by probe methods. Figure 2 shows the temporal behavior of radial profile of the electron concentration. As it seen, plasma parameters in this discharge mode undergo periodic time fluctuations. The period of such fluctuations is about 0.25 ms. This value is close to the period of striations (0.4ms) which was observed experimentally [2]. In our calculations processes of transport along the discharge tube, as well as longitudinal non-local effects were not taken into account. The correct quantitative description of striations is possible only in 2D (axial-radial) model. The drift of the electrons could increase the period of such fluctuations.

Figure 3 shows the electric field $E$ and electron temperature $T_e$ at the tube axis as functions of time. We can see here a well-defined periodical structure of the fluctuations. We can see that each new fluctuation begins from jump of the electric field. In turn, it causes increase in the electron temperature and in the concentration of metastable atoms.
We carried out systematic calculations of the transition between diffuse and constricted-stratified modes of the discharge. This transition is interesting for two reasons: first, at this transition the phenomenon of a hysteresis in VCC is observed; secondly, it is a serious problem for discharge models to obtain a decay of the constricted mode and a disappearance of the fluctuations at the transition to the diffuse mode. In our case the mechanisms taking out the discharge from the constricted (constricted-stratified) mode, are the effects of the radial non-local formation of the EEDF. It should be noted that this radial non-locality of EEDF tail is of different kind than axial non-locality of EEDF tail, considered in [5,11] as a source of ionization instability (striations). The constricted-stratified discharge by its nature is closer to the constricted mode, than to the stratified.

Figure 1. Radial profiles of the electron concentration in the diffuse (10 mA, curve 1) and the constricted (180 mA, curve 2) modes at pressure of 40 Torr.

Figure 2. Electron density, electric field and electron temperature at the discharge tube axis as a function of time (current is 30 mA).

Figure 3. Electric field $E$ (1) and electron temperature $T_e$ (2) at the discharge tube axis as a function of time (current is 30 mA).
Figure 4 shows the calculated current-voltage characteristics of a dc discharge in argon in the conditions [2]. The characteristic demonstrates a well-pronounced hysteresis effect. To the best our knowledge, until now, there were no publications in which the hysteresis transition between the diffuse and constricted-stratified discharge modes was obtained numerically. It is seen that, the calculated current-voltage characteristics well reproduces the measured one and both the direct transition from the diffuse to the constricted-stratified mode and the reverse transition occur at the same values of the discharge current as in the experiment [2]. This indicates that the model takes into account correctly the basic processes leading to the discharge constriction and bringing the system out of the constricted mode.

At the extremely high currents (for the case under study, 180 mA and higher) the discharge smoothly passes from the constricted-stratified mode into the constricted mode. We traced the transformations of the structure and plasma parameters of the constricted-stratified mode with the discharge current. A transition (at ~180 mA) from the constricted-stratified mode to the constricted mode occurs smoothly (without any jumps). As it is seen from figure 4, the voltage jumps and hysteresis effects are not observed here, contrary to the transition from the diffuse to the constricted-stratified mode. As all the striations in noble gases are moving, we can say a length of this region when we are speaking about duration of the phase of high or low electron density. In the constricted-stratified mode an increase in the discharge current leads to increase in the period of fluctuations. Thus the increase in the length (duration) is specific to the region with the high electron concentration (such as regions at t=(0÷1ms) and (3÷4ms) in figure 2) and the length of the region with low
electron concentration is decreased. Thus, the ratio of the lengths of the high and low electron concentrations regions (~0.5:0.5 at 30 mA) is steadily increased with discharge current and reaches ~1:0 at 1–180 mA and the discharge passes to the constricted mode without any fluctuations. So, at value of the discharge current ~180 mA, the adjacent regions (with high electron concentrations) flow together. The nature of the fluctuations in the constricted-stratified mode is in the inconsistency between the ionization rate and the electron energy gain: e.g., low electric field and high ionization rates in the phase of the high electron density. This phase lasts until the energy delivery from the body of the EEDF to the tail of the EEDF by e-e collisions takes place. In our calculations, we observed the quasi steady state $T^* \sim 0.8$ eV against the background of the decrease in $T_e$ from 1.5 down to 1.0 eV.

4. Conclusion
In this work, a one-dimensional self-consistent model for describing high-pressure dc discharges in noble gases has been developed. The model includes the continuity equations for charged and excited particles, the heat conduction equation for the neutral gas and electron energy conservation equation, and Poisson's equation for the radial field, as well as equations for the temperatures of the low- and high-energy parts of the EEDF. Three discharge modes have been considered: the diffuse, constricted-stratified, and constricted ones. The developed theoretical model of a dc discharge in all these modes has allowed for the first time, to our knowledge, to obtain periodic fluctuations of plasma parameters for the constricted-stratified mode without any artificial assumptions. A transition from the diffuse to the constructed-stratified mode occurs by a jump and is accompanied by a hysteresis effect. This effect consists in that the transition from the diffuse to the constricted-stratified mode (as the discharge current is increased) and the reverse transition (as the current is decreased) take place at different discharge currents. A transition from the constricted-stratified mode to the constricted mode occurs smoothly, without any jumps. The developed model allowed to obtain also both of these transitions (hysteresis transition between diffuse and constricted-stratified modes and smooth transition between constricted-stratified and constricted modes).

Acknowledgments
We are pleased to acknowledge support from RF government for Key Science Schools grant № 133.2008.2.

5. References
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