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The role of high-energy electrons in the formation of the transverse profile of high-speed ionization wave fronts in gases

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Abstract. A comprehensive experimental study of the spatio-temporal structure of the fronts of discrete, high-speed ionization waves (HSIW) in shielded discharge tubes filled with inert gases is carried out. It is shown that the ionization wave front at low gas pressures (below 1 Torr) has a volumetric structure, but at gas pressures above 10 Torr assumes a cylindrical form, compressed into the dielectric boundary of the discharge tube. The high-energy electrons generated at the ionization wave front have a significant impact on its structure and their energy relaxation modes. Evaluations of the energies of electrons accelerated at the HSIW front are provided along with an analysis of the influence of the energy relaxation regimes of the high-energy electrons on the structure and dynamics of the development of the ionization wave front in the shielded dielectric discharge tubes.

1. Introduction

High voltage nanosecond discharges, in which internal electric fields exceed the critical value required to transfer electrons in continuous acceleration mode, are characterised by intensive generation of high-energy electrons in the electrical breakdown of the gas. There exist various discharge systems, in which electron beams or a group of high-energy electrons are formed during electrical breakdown in a gaseous environment [1-9]. One such type of discharge is the nanosecond electrical discharge in long shielded dielectric tubes, which is developing under conditions of the formation and propagation of high-speed ionization waves [7–11]. Such discharges have a number of features related to the mechanism of gas breakdown by high-speed ionization waves. This primarily relates to the spatio-temporal structure of the discharge, the complexity of which is due to non-simultaneity and heterogeneity of gas ionization along the discharge tube. It is known, the application of high voltage pulses with a nanosecond rise time leads to the formation of the ionizing potential gradient waves in the discharge tube propagating from the high voltage to the grounding electrode with a velocity of 10^8–10^{10}cm/s. If the high-speed ionization wave front duration is significantly lower than the ionization wave propagation time from one electrode to another, the gas excitation along the discharge tube takes place in the direction from the high-voltage to the grounded electrode with a delay determined by the HSIW velocity. The localisation of a strong electric field at the HSIW produces the final source of high-energy electrons.

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The aim of this study is to investigate the role and energy relaxation modes of high-energy electrons in the formation of the spatio-temporal structure of the ionization wave front in shielded dielectric discharge tubes filled with inert gases.

2. Methods and experimental techniques

In order to study the formation dynamics of the high-speed ionization wave front structure, the authors of this paper studied nanosecond discharges in shielded glass tubes fitted with internal electrodes having a length of 50 cm and an internal diameter of 8 mm. A schematic view of the gas-discharge system is represented in figure 1. Aluminium electrodes were constructed in the form of hollow cylinders, through which the optical discharge radiation was recorded along the tube. Discharge tubes were placed inside a metal screen having a diameter of 2 cm. In order to record the electrical characteristics of the HSIW, several capacitive sensors were placed along the discharge tube at predefined distances from each other. In order to eliminate the influence of edge effects, edge sensors were installed on the borders of the screen at a distance greater than double the diameter of the metal screen. A light sensor in the form of a length of optical fibre was installed next to each capacitive sensor in order to study movement of the optical radiation of the high-speed ionization wave front along the tube. The signal from a 50-Ohm low-induction resistance shunt, included between the screen and the grounded electrode, was used for measuring the rate of discharge. A wideband digital recording device with a frequency band of 350 MHz was used as a recording system.

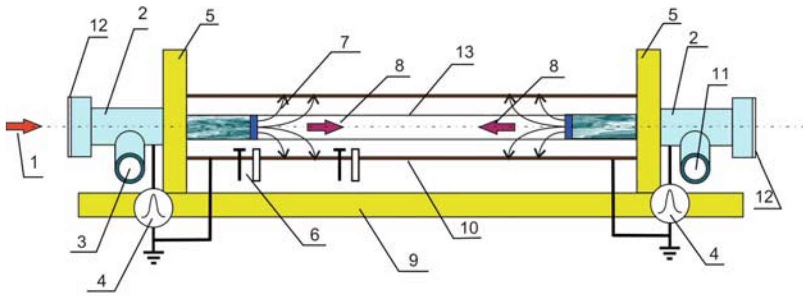

Figure 1. Flowchart of the discharge tube and the formation of HSIW. 1 – laser beam; 2 – hollow electrodes; 3 – input gas valve; 4 – nanosecond pulse generator; 5 – discharge limiters (isolator); 6 – capacitive and optical sensors; 7 – electric field lines; 8 – direction of HSIW propagation; 9 – stand (isolator); 10 – metallic screen; 11 – output valve of vacuum pump; 12 – quartz windows; 13 – quartz tube.

A block diagram of the experimental setup is shown in figure 2. A high-voltage pulse generator (VPG) for the formation of HSIWs was assembled on the transformer circuit according to a coaxial design in which the primary winding was composed of four turns and the secondary of two coils with 12 turns each. A TGI-130/10 ceramic thyratron was used as a switching device in the VPG. This generator allows two synchronised high-voltage pulses to be simultaneously produced with adjustable amplitude up to 40 kV, a repetition rate of 100 Hz, and a voltage pulse duration at half maximum of about 100 ns.

The system of capacitive and optical sensors allowed the velocity of HSIW propagation to be determined by measuring the delay time of signals from any two sensors. In addition, an analysis of the amplitude of the signals from the capacitive sensors allowed the attenuation coefficients of the HSIW to be determined in the process of propagation of ionization wave along the tube.

The density of the electrons behind the HSIW front was evaluated relative to the magnitude of the reverse shunt current and HSIW damping coefficient. The voltage across the discharge gap was measured using a calibrated voltage divider.

The transverse spatiotemporal structure of the HSIW front was investigated using a high-speed photographic recorder based on the ICCD of a Princeton Instruments PI-MAX3 camera model, allowing the capture of images with exposure times of 2 ns showing the optical emission discharge structure of a cross-section of the discharge tube.

Since metastable atoms play an important role in the process of gas ionization in the inert gases, the occupation dynamics of the metastable states of neon and helium atoms was investigated separately, with a nanosecond time resolution for the HSIW front, using the laser absorption spectroscopy method. The methodology of such studies is described in [8, 9]. In the present work, a tunable Nd:YAG model LQ629-100 laser with a LP601 parametric light generator generating the wavelengths between 410 to 680 nm was used as a source for probing the optical radiation plasma.

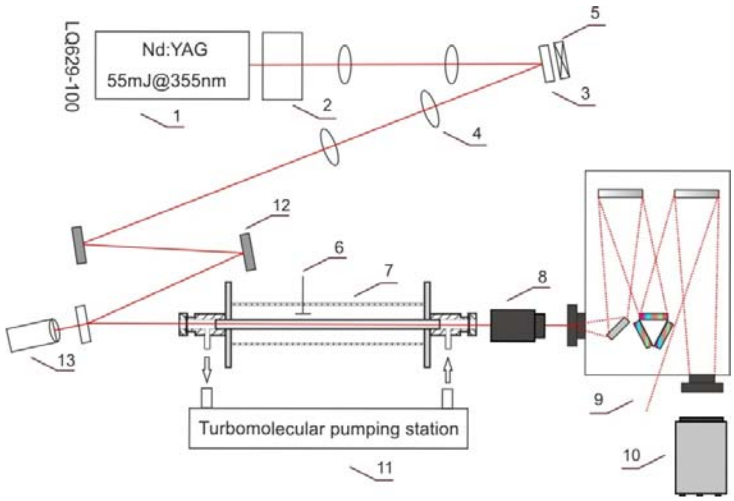

Figure 2. Block diagram of the experimental setup. 1 – Nd: YAG LQ629-100 laser; 2 – LP601 parametric light generator with a range of 410 to 680 nm wavelength tuning generation; 3 – glass plate; 4 – lenses; 5 – beam lock; 6 – capacitive sensors mounted along the discharge tube; 7 – discharge tube; 8 – photographic objective; 9 – MS7504i spectrograph; 10 – CCD camera; 11 – turbomolecular pumping station; 12 – mirrors; 13 – photocathode for controlling the laser pulse characteristics.

3. Experimental study

The transverse structure of the ionization wave front is highly dependent on the distribution of the electric field over the front, i.e. the modes and mechanisms of high-energy electron formation and relaxation. In order to obtain information about the transverse structure of the HSIW front, a series of experimental studies was carried out on the HSIW transverse profile by means of high-speed photographic recording of the transverse distribution of the optical radiation from the front in time-lapse mode. The time resolution was about 2 ns and the exposure of each frame was between 5 and 20 ns, depending on the development stage of the ionization wave. These studies were carried out in helium, neon, and argon gases at pressures ranging from 1 to 100 Torr and voltage pulse amplitudes of 40 kV, using a Princeton Instruments PI-MAX3 ICCD camera model. Synchronization was performed from the start of the HSIW near the high-voltage electrode and the opening of the electro-optic shutter of the PI-MAX3 high-speed camera. In this way, a set of optical cross-sectional pictures of the high-speed ionization wavefront was obtained in helium, neon, and argon gases at different pressures and voltage pulse amplitudes.

The studies showed that there are certain regularities in the formation of the transverse structure of a high-speed ionization wave.

Figure 3 presents typical photographs of the cross-section of the discharge for four time moments following the start of the HSIW in neon near the high voltage electrode and the corresponding contour

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lines of equal intensity. These photos and the corresponding optical radiation intensity distributions from different regions of the HSIW front demonstrate that at gas pressures above 10 Torr near the boundary of the discharge tube, there is a region of intensified gas ionization. Its thickness is less than 1 mm but optical radiation from the central regions of the plasma waveguide is almost absent. Furthermore, it should be noted that the thickness of the reinforced area of ionization is virtually unchanged in proportion to the degree of excitation and ionization, from which it can be concluded that the ionization shock waves are generated towards the centre of the discharge tube during propagation.

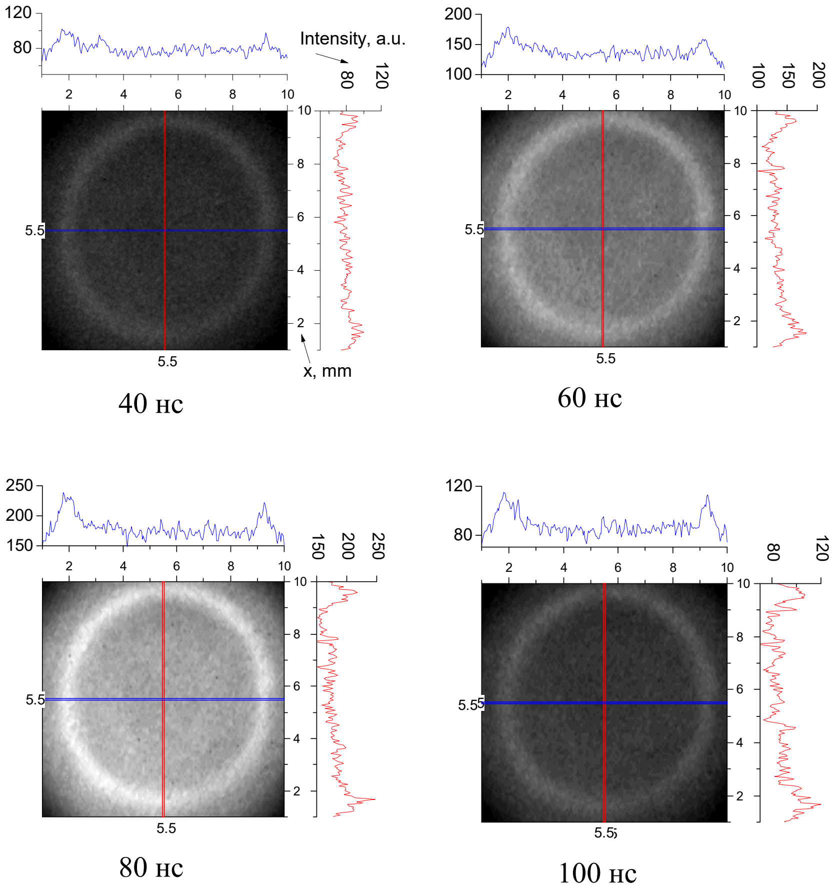

Figure 3. Synchronised time-lapse high-speed photography of the high-speed ionization wavefront in neon in the cross section of the plasma waveguide under the formation conditions of two adverse ionization waves. Pressure of neon – 25 Torr; amplitude of voltage pulses – 28 kV; exposure time – 5 ns.

The electrodes in the discharge tube are supplied with voltage pulses of an opposite polarity. The points in time from the beginning of the glow are given below the photos.

Figure 4 shows the analogous synchronised time-lapse photographs of the high-speed ionization wavefront in neon at different times at a gas pressure of 1 Torr. As it is seen from these pictures, at low pressures, the degree of ionization and excitation of the plasma gas in the centre of the plasma waveguide is higher than at the boundary of the discharge tube and the HSIW is formed and distributed throughout the volume of the discharge tube.

The electrodes in the discharge tube are supplied with voltage pulses of opposite polarity. The points in time from the beginning of the glow are given below the photos.

The analysis and systematisation of the experimental data allows us to establish the general laws of formation of the transverse structure of the high-speed ionization wavefront in plasma waveguides, provided with hollow cylindrical electrodes. In particular, the following patterns are noted:

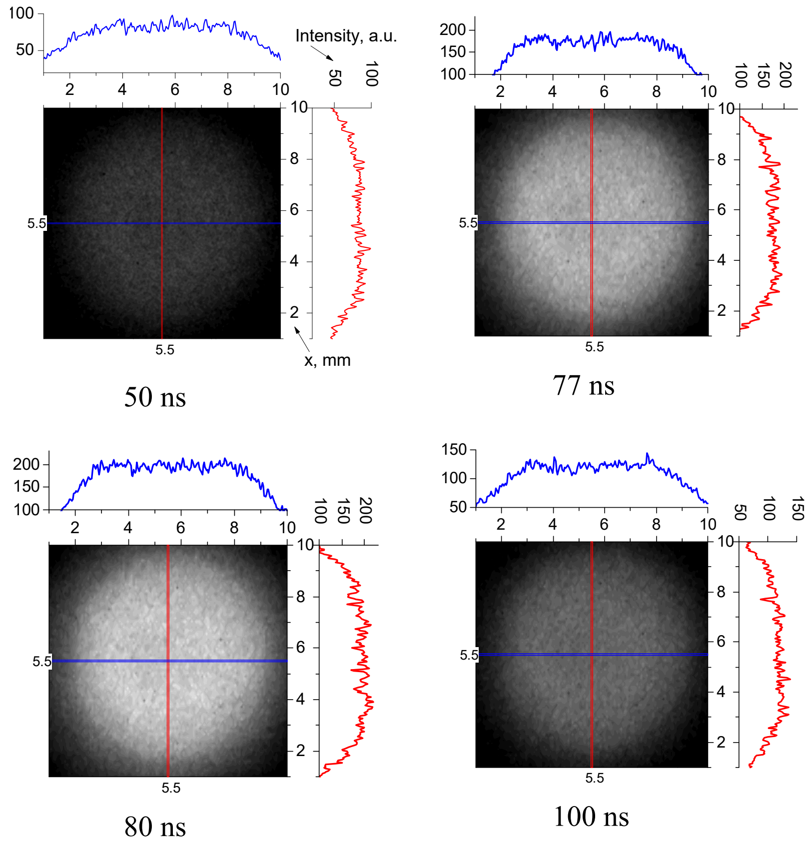

Figure 4. Synchronised time-lapse high-speed photography of the high-speed ionization wavefront in neon in the cross section of the plasma waveguide under the formation conditions of two adverse ionization waves. Pressure of neon – 1 Torr; amplitude of voltage pulses – 28 kV; exposure time – 20 ns.

1. For all three gases at gas pressures below 1 Torr, a HSIW is formed and distributed throughout the volume of the discharge tube across the whole range of investigated voltage amplitudes;
2. At gas pressures below 0.1 Torr, a significantly uniform distribution of the integrated intensity of the optical radiation becomes established in the cross section of the discharge tube;
3. With increasing gas pressures, the homogeneous structure of the high-speed ionization wavefront transfers into a grazing form via the dielectric surface with the localisation of the highly ionized region near the wall in the cylindrical layer having a thickness of less than 2 mm.
4. In proportion to the operating time of the degree of ionization of the gas, the thickness of the ionized gas region hardly changes and ranges within a value of 1 mm. With reduction of gas pressure to levels below 1 Torr, the thickness of ionized gas increases to a few millimetres.
5. The pressure transition boundary of the volumetric structure of the HSIW front to the grazing structure grows from argon to neon and further to helium. In argon, the HSIW front transitions from volumetric to grazing form along the surface of the dielectric gas at pressures above 0.5 Torr; in neon, this takes place at gas pressures above 3 Torr; in helium – at gas pressures above 10 Torr. With

an increase in the amplitude of the voltage pulses, the pressure boundary at the transition of the volumetric form of the HSIW reduces to grazing form.

With grazing form of the HSIW front, the maximum intensity of the optical radiation near the walls of the discharge tube can exceed the analogous quantity from the central regions of the discharge tube by up to 5-6 times.

The dynamics of the operating time of the metastable atoms of inert gases was investigated under similar conditions. The plasma density was measured by forming a narrow laser beam to probe metastable atoms in the central portion of the discharge tube and in the vicinity of its borders. Figure 5 shows the time dependence of the measured density of metastable neon atoms. The maximum value of the density of metastable atoms in the HSIW front appears to be comparable with the maximum value of the electron density, which is a characteristic of stepwise ionization of inert gases in nanosecond discharges.

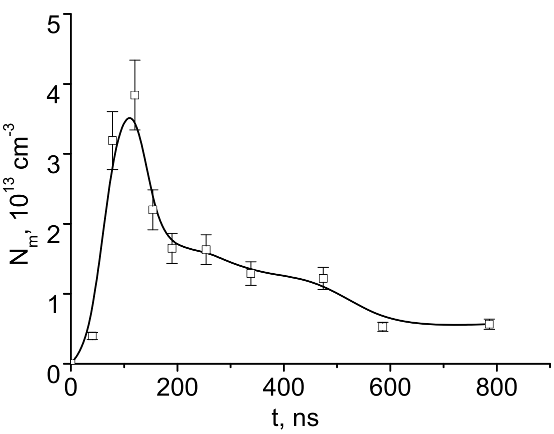

Figure 5. Time dependency of the density of excited neon atoms in the $3s^3P_1$ state, measured along the centre of the tube. Pressure of neon – 2 Torr; amplitude of voltage pulses – 36 kV.

4. Discussion of experimental results

With the wave function of electrical breakdown of the gas, almost all the electric field is concentrated in the ionization wavefront. In this area of intensified electric field, free electrons are accelerated and gain the energy ε, which can be estimated from the following equation [1,10]: $\frac{d\varepsilon}{dx} = eE - F(\varepsilon)$, where $F(\varepsilon) = \frac{2\pi e^4 ZN}{\varepsilon}\ln(\frac{2\varepsilon}{I})$ is the so-called effective ionization stopping power, I is the average energy of inelastic losses of electrons, and E is the electric field strength. Under the condition $eE > \max(F)$ of a proportion of the electrons being able to pass into the regime of continuous acceleration, high-energy electrons are formed, according to the known "runaway electron" effect.

The characteristic size of the region of intensified field (the geometric length of the HSIW front) is of the order $x_0 \sim \tau\upsilon$, where τ is the duration of the leading edge of the HSIW and υ is the velocity of the HSIW. With negative polarity, high-voltage pulses applied to the electrodes of the plasma waveguide, and the ionization wave characteristics are mainly determined by the current high-energy electrons. The processes in the HSIW front are similar to the processes at the "head" of the electron beam propagating through the gas. In this case, the ionization wavefront acts as a moving virtual cathode, emitting high-energy electrons with energies of $\varepsilon_b \sim m\upsilon^2/2$. In particular, in [9, 10] it is shown that the critical electron velocity value near $\upsilon_0 = \sqrt{\frac{2.72I}{m}}$ the electrons undergoes relaxation oscillations under the condition:

$$\frac{E_0}{N} > \frac{\beta\gamma}{2.72\alpha} = \frac{2\pi e^3 z}{2.72I} \quad (1)$$

It means that the energy of high-energy electrons in the HSIW front fluctuates near the value $\varepsilon_b \sim m\upsilon^2/2$.

Table 1 shows the values of the electric field at the wave front ionization, the HSIW parameters, and energy of electrons accelerated at the HSIW front in neon when the ionization waves have a negative polarity. These values are calculated from the waveform of the electrical potential gradient measured with calibrated capacitive sensors for the VPG, with voltage pulses having a duration of about 100 ns.

Comparing of the calculated values of the reduced electric field strength with the critical values for continuous acceleration [1, 4, 10, 12], we can conclude that the conditions for continuous and efficient acceleration of electrons forming high-energy electrons on the HSIW front with a voltage pulse duration of about 100 ns for the VPG exist only at gas pressures below 1 Torr. At the same time, the energy of the high-energy group of electrons is of the order of several tens of eV; at these energies of electron excitation, the ionization rates of helium and neon atoms also have maximum values.

High-energy electrons generated in the HSIW front, carry out effective electronic excitation and ionization of the gas atoms, thereby gaining free electrons and excited atoms at the ionization wave front. In addition, a proportion of the high-energy electrons also produce preliminary ionization of the gas at the negative polarity HSIW front. The spatial dimensions of the relaxation region of the high-speed electron energy affect the structure and the uniformity of the HSIW front. At the front of the ionization wave, the function of the electron energy distribution function (EEDF) consists of two parts – fast, with the energy $\varepsilon_b \sim m\upsilon^2/2$, and slow, consisting mainly of a plasma formed by secondary electrons. It is known that a local or non-local EEDF formation mode can be analyzed by introducing a relaxation parameter [13, 14]:

$$k(\varepsilon) = (\nu_e + \delta\nu_a + \nu^*)\tau_r \quad (2)$$

where ν_e is the frequency of inter-electron collisions; $\delta = 2m/M$; ν_a is the frequency of elastic collisions between electrons and atoms; ν^* is the frequency of inelastic collisions of electrons with atoms; τ_r is the time of withdrawal of electrons from the ionization region as a result of transport phenomena. If $k(\varepsilon) \gg 1$, the energy of the high-energy electrons is relaxed in the ionized volume, without ranging beyond the HSIW front. A significant part of the energy of such electrons is expended on the excitation and ionization of the gas atoms in the specified area.

Table 1.

P, Torr	U, kV	E, V/cm	E/P, V/(cm · Torr)	τ, 10^{-9}s	υ, 10^8cm/s	x_0, cm	ε, eV
1	28	1481	1481	54	3.5	18.9	35
1	40	1894	1894	48	4.4	21.1	55
10	28	1221	122	62	3.7	22.9	39
10	40	1867	187	51	4.2	21.4	50
20	28	1275	64	61	3.6	22.0	37
20	40	1429	71	56	5.0	28.0	71
60	28	1176	20	70	3.4	23.8	33
60	40	1587	26	60	4.2	25.2	50

Such a regime can be formed at moderate gas pressures, when the region of enhanced ionization is localized in a small layer near the discharge tube wall, where the high-energy electrons have been initially formed. In the case of the volumetric form of the high-speed ionization wave front (for the considered conditions at gas pressures below 1 Torr and low amplitudes of voltage pulses), the flux of fast electrons in the discharge tube wall is small, and the value of the wall potential in the particular case of the Maxwell distribution of the main groups of electrons is determined by the average energy of the plasma electrons [13]:

$$\Delta V = \frac{kT_e}{e}\ln\left[\frac{\sqrt{M}}{3\sqrt{\pi m}}\right] \sim \frac{kT_e}{e} \quad (3)$$

When $k(\varepsilon) \ll 1$, if $e\Delta V < \varepsilon_b$, the faster electrons depart to the wall in free diffusion mode, and the high-speed EEDF part the energy peak. The withdrawal of these electrons to the walls can increase the value of the near-wall potential to the value of the order $\frac{\bar{\varepsilon}_b}{e}$, since for the fulfillment of conditions of the quasi-neutrality of plasma, in this case, it is necessary to withhold a proportion of the fast electrons in the volume. As a result, fast electrons being locked in volume leave this energy region, which is also determined by collisional processes in the volume and forms the volumetric form of the high-speed ionization wave front structure. In this case, as in $k(\varepsilon) \gg 1$, a continuous electron spectrum is formed, and the energy of fast electrons is expended in the excitation and ionization of the gas atoms in the entire volume of the discharge tube.

5. Conclusions

Thus, the results of the pilot study and our analysis show that under the considered conditions, the HSIW front has two formation modes – namely the volumetric form of the HSIW structure (when gas pressures are below 1 Torr) and a cylindrical shape pressed towards the walls of the discharge tube (at gas pressures above 10 Torr). At the HSIW front, the high-energy electrons are generated, their energy relaxation has a significant impact on the structure of the HSIW front. In the formation and propagation of the cylindrical HSIW front, the spatial distribution of plasma parameters attains cylindrical symmetry with a maximum density of excited atoms near the walls and the minimum in the centre of the tube. The size of the wall thickness of the plasma ionization is determined by the maximum length of the energy relaxation of a group of high-energy electrons when, in the process of ionization growth, the shock waves towards the sides of the discharge tube do not form.

Acknowledgments

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