The dynamics of the spatiotemporal distribution of excited atoms in a nanosecond discharge with a slot cathode

N A Ashurbekov\(^1\), K O Iminov\(^1\), G S Shakhshinov\(^1\) and M Z Zakaryaeva\(^{1,2}\)

\(^1\)Dagestan State University, M. Gadjiev St, 43a, Makhachkala, 367001, Russia
\(^2\)Institute of Physics, DFRC of RAS, M. Yaragsky St, 94, Makhachkala, 367015, Russia

E-mail: nashurb@mail.ru

Abstract. The work is devoted to the study of the spatiotemporal dynamics of the production of excited atoms in an extended nanosecond discharge with a slot cathode in neon at medium gas pressures. The authors experimentally investigated the frame-by-frame dynamics of the spatiotemporal formation of the discharge optical irradiation with an exposure time of 5 ns and time intervals between frames of 2 ns. Under similar conditions, the concentration of excited neon atoms at metastable levels with a time resolution of about 10 ns was measured by laser absorption spectroscopy, and the current-voltage characteristics of the discharge were experimentally determined in a wide range of amplitudes of voltage pulses and gas pressures in the range of 1–60 Torr. To analyze the kinetic processes in the plasma source under study, numerical simulation of ionization processes in the Comsol Multiphysics software environment was performed using a special Plasma module.

1. Introduction
Recently, studies of inhomogeneous gas-discharge plasma have gained particular relevance in the scientific and applied aspects due to its wide application in a variety of plasma technologies and devices [1–3]. Discharges of this type are widely used in light sources, lasers, and other gas-discharge devices [4, 5]. In creating powerful pulsed gas-discharge optical irradiation sources, information on the concentrations of excited atoms and their distribution in the discharge gap is important. The rate of excitation and ionization of atoms under such conditions depends on the electron distribution function (EDF). Probe methods for measuring the EDF at high electron energies exceeding the excitation threshold do not allow to determine the presence of fast electrons in the discharge with sufficient accuracy due to the small signal-to-noise ratio [6]. A reliable source of information on fast electrons are excited atoms formed as a result of inelastic collisions. In view of this, it is of interest to investigate the spatiotemporal dynamics of the formation and distribution of the density of excited atoms in a transverse nanosecond discharge with an extended slot cathode [7].

The aim of this work is to numerically simulate the spatiotemporal dynamics of the density distribution of excited atoms in a limited nanosecond discharge with a slot cathode in neon at medium gas pressures and to compare the findings with experimental results.

2. Experimental part and results
The nanosecond discharge occurred in a quartz tube between aluminum electrodes located in parallel at a distance of 0.6 cm from each other. The anode was a flat plate 5 cm long, 2 cm wide and 0.5 cm thick.
The cathode was a cylindrical rod 5 cm long and 1.2 cm in diameter, with a longitudinal cavity cut in the form of a slit 0.2 cm wide and 0.6 cm deep [8]. The discharge area between the cathode and the anode was confined on both sides by fiberglass dielectric plates; as a result, it was shaped as a rectangular parallelepiped 5 cm long, 1.2 cm wide and 0.2 cm high.

The current and voltage of the discharge were measured with an ohmic shunt and a calibrated voltage divider. To study the spatiotemporal dynamics of the development of a nanosecond discharge, a PI-MAX3 high-speed camera was used. The concentration of excited atoms at various levels was measured by laser absorption spectroscopy with nanosecond time resolution. The MS7504i Monochromator/Spectrograph was used as a spectral device; the signals from the photomultiplier tube (PMT) output were fed to a Tektronix TDS2024B oscilloscope, which was also used to measure the electrical characteristics of the discharge. The measurement system was synchronized with the discharge current (by triggering the TGI1-500/16 thyratron) using a special Tektronix AFG 3022B pulse generator (figure 1).

Figure 1. The block diagram of the experimental setup. 1) Discharge chamber; 2) Dye laser; 3) Monochromator; 4) PMT; 5) CCD camera; 6) Oscilloscope; 7) Computer; 8) Voltage generator; 9) Pulse generator; 10) Eximer laser; 11) L – focusing lens; 12) A, C – anode, cathode.

The electrical characteristics, as well as the spatiotemporal dynamics of the formation of the structure of a transverse nanosecond discharge and the concentration of excited atoms at metastable levels of neon in a discharge plasma at a gas pressure in the chamber, were experimentally investigated.

In figure 2 (a) as an example, typical oscillograms of the electrical characteristics of the discharge are given. It can be seen from the figure that the breakdown occurs at the leading edge of the voltage pulse until it reaches its maximum value. The duration of the leading edge of the burning voltage pulse is approximately 100 ns, and the maximum amplitude due to the voltage doubling circuit used in the voltage generator reaches $U_{br} \sim 1800$ V. Moreover, the discharge current reaches a maximum of $I_{br} \sim 270$ A, while the current pulse at half maximum is only 50 ns.

Oscillograms of current and voltage on the discharge electrodes make it possible to estimate the concentration of free electrons in the discharge. The electron concentration can be estimated from the plasma conductivity using the well-known formula for the discharge current density

$$j_{br} = en_e \nu_{dr},$$

where $e$ is the electron charge, $n_e$ is the concentration of free electrons, $\nu_{dr}$ is the electron drift velocity. The current density $j_{br} = I_{br}/S = 270$ A/cm$^2$ was calculated from the experimental value of the current strength at the maximum $I_{br} = 270$ A and the discharge cross-sectional area $S = 1$ cm$^2$. The
electron drift velocity of $v_{dr} \sim 3.6 \cdot 10^7 \text{ cm/s}$ was determined from the table based on the reduced electric field strength $E/N$, where $N$ is the concentration of gas atoms $[9]$. When determining the values of $E$ in the plasma column, the value of $U_{br}$ was taken at the maximum $I_{br}$ and it was taken into account that in a discharge with a hollow cathode, almost all the voltage applied to the gap decreases in the area of the cathode potential drop (CPD). For estimates, we can take the value of the voltage drop across the plasma column $U_p \sim U_{br}/3$ $[10]$. Estimation by formula (1) for the conditions of figure 2 gives a value of $n_e \sim 4.5 \cdot 10^{13} \text{ cm}^{-3}$.

**Figure 2.** Oscillograms of current pulses and discharge voltage (a) and the dependence of the concentration of metastable neon atoms on time (b) at neon pressure $p = 10 \text{ Torr}$.

A study of the absorption spectra against the background of a continuous spectrum of a dye laser makes it possible to determine the concentrations of metastable and excited atoms in a pulsed discharge of nanosecond duration. The oscilloscope recorded the contour of the spectrum of broadband dye laser irradiation and the absorption profile of laser irradiation in plasma on spectral lines corresponding to the NeI(3s$^1$P$_1$ - 3p$^3$D$_2$) $\lambda = 650.6 \text{ nm}$, NeI(3s$^1$P$_0$ - 3p$^3$D$_1$) $\lambda = 653.2 \text{ nm}$ transitions. Then, using the special program compiled in the Matchad environment, the areas of the corresponding contours and the total absorption were calculated. Using the obtained values of the total absorption from the calculated curves $[11]$, the optical plasma thicknesses $\chi_0$ were determined using the formula

$$N_m = \frac{1}{2} \sqrt{\frac{\pi}{\ln 2}} \frac{m_B \cdot c}{\pi \cdot e^2 \cdot f_{mn}} \Delta \nu_0 \chi_0$$

where $\Delta \nu_0$ is the Doppler line width and $f_{mn}$ is the oscillator strength of the corresponding spectral transitions.

Figure 2 (b) shows the time dependences of metastable atoms concentration for two energy levels of a neon atom. It can be seen that the maximum concentration of excited atoms NeI(3s$^1$P$_1$) is reached at times $t \sim 130 \text{ ns}$ after the start of the current pulse, and at the maximum it makes $\sim 3 \cdot 10^{13} \text{ cm}^{-3}$.

The results obtained show that the jump in the populations of metastable states at the initial stages of a nanosecond discharge can exceed the quasi-stationary values by an order of magnitude. In transverse nanosecond hollow-cathode discharges, high-energy electrons are generated $[12]$. These electrons in the process of collisions with atoms lead to intensive population of metastable states, since their population rate significantly exceeds the rate of direct ionization $[13]$. Only as the energy of fast electrons relaxes, the processes of stepwise ionization from metastable levels do start, limiting the populations of these levels. Therefore, due to the high population rate of low-lying excited states in a transverse limited
nanosecond discharge with a hollow cathode, the concentration of excited atoms at metastable levels reaches a value comparable to the electron density in the discharge (figure 2 (b)).

An investigation of the spatiotemporal dynamics of the formation of optical discharge irradiation allows to establish the characteristics of its spatial structure development at various stages of a limited nanosecond discharge in neon. In the discharge gap, the first glow appears at the surface of the anode. Further, the luminescence, propagating to the cathode, penetrates into the cathode cavity and is localized along the walls of the rectangular cavity, while in the gap between the electrodes, it concentrates at the axis of the gap (figure 4 (a)). Optical irradiation focusing at the anode surface is observed, while the structure of the discharge in the gap takes a triangular shape with a base on the cathode surface (figure 4 (a)). The formation of such an original and complex spatial structure of the discharge is associated with the spatial distribution of the electric field in the cavity and in the gap and is caused, among other things, by surface phenomena at the plasma-insulator interface.

3. Model of ionization processes
Numerical simulation of the problem is carried out in the Comsol Multiphysics software environment with the use of a special Plasma module. The geometry of the simulation area is selected proceeding from the actual dimensions of the discharge chamber and the electrode system (figure 3).

![Figure 3. The area of discharge simulation.](image)

The simulation task is to study the dynamics of the formation and development of a nanosecond discharge with a complex cathode geometry and to investigate the spatiotemporal structure of the distribution of the main parameters of the discharge in neon.

In the field of modeling, a self-consistent system consisting of the standard Poisson equation for calculating the plasma potential, the drift-diffusion equation for electron density, the extended form of the Maxwell-Stefan equations for the transfer of heavy particles, the energy balance equation for electrons, the kinetic equation for EDF modeling is solved [14, 15].

To set the shape and parameters of the electric field potential, the \( U_{br} \) impulse of the burning voltage of the discharge was digitized. To align the discharge current values with the experimental values, ballast resistance was introduced into the model in accordance with the \( U = U_0 - I_p \times R_b \) equation.

4. Simulation results
A numerical simulation of the dynamics of the formation and development of the ionization wave front and the distribution of the electric field potential and the concentration of charged particles in the discharge gap and in the cathode cavity during ionization development was performed. Under the same conditions, the spatiotemporal dynamics of the density distribution of excited neon atoms was calculated both along the discharge axis and transverse in the middle of the cavity and in the center between the electrodes at a working gas pressure \( p = 10 \) Torr and at \( U_{br} \sim 1800 \) V values of the amplitude of the burning voltage pulse. The initial concentration of charged particles was taken equal to \( 10^8 \) cm\(^{-3}\). It was uniformly distributed in the gap between the electrodes and inside the cathode cavity, which corresponds approximately to the residual charge under a pulse-periodic mode of gas ionization.

The simulation results show that an ionization wave directed towards the cathode is formed at the anode surface. The ionization wave moves at a speed of \( 2 \times 10^7 \) cm/s and reaches the cathode in 30 ns. About 100 ns after the start of the breakdown (triggering of the thyatron), the electron concentration reaches \( 10^{12} \) cm\(^{-3}\) and the plasma penetrates into the cathode cavity. The next stage is the formation of
the cathode layer and the production of charged particles inside the cavity. Electrons emitted from the side surfaces of the cavity in the cathode, without collisions, pass through the CPD area, get accelerated and, colliding with atoms, excite and ionize them. The excitation and ionization of atoms occurs in a narrow area along the inner surface of the cavity, where the energy of accelerated electrons is relaxed. As a result, a peculiar discharge structure with an uneven distribution of the plasma density in the cavity and in the gap between the electrodes is formed (figure 4 (b)).

Figure 4. Optical pattern of the discharge (experiment) (a) and the results of the spatial distribution of electron density in the discharge gap modeling (b) for the conditions of figure 2.

It is interesting to note that the defining characteristics of the distribution of the intensity of the optical irradiation of the discharge in the experimentally obtained optical pattern (figure 4 (a)) are in qualitative agreement with the results of numerical simulation of the charged particles density distribution (figure 4 (b)). The optical pattern and the simulation results (figure 4) are synchronized in time and obtained 200 ns after the application of voltage to the electrodes.

Of particular interest are the results of excited atoms distribution modeling. The spatial profile of the concentration distribution of excited neon atoms in the discharge has a complex structure. At the beginning of the breakdown, the processes of electronic excitation of atoms occur mainly in the discharge gap between the electrodes. The concentration of excited atoms in the gap gradually increases, and after 150 ns, the density of excited atoms reaches its maximum at the entrance to the cathode cavity and makes $\sim 10^{13}\text{cm}^{-3}$. Subsequently, the maximum density of excited atoms moves to the cathode cavity, due to the growth of the processes of excitation and ionization of atoms in the cavity. After the cathode layer is formed in the cavity, the processes of excitation and ionization are localized at the cathode layer, which leads to a rapid increase in the density of excited atoms at the cathode layer. Their characteristic spatial distribution with a sharp density peak of $\sim 9\cdot10^{12}\text{cm}^{-3}$ at the base of the cavity is established after about 400 ns.

5. Conclusion

Thus, numerical modeling of the processes of formation and development of a transverse limited nanosecond discharge with an extended hollow cathode in neon allows us to conclude that an ionization wave is formed at the anode surface and propagates to the cathode at a speed of $2\cdot10^7\text{cm/s}$. In this case, the ionization wave propagates in the center of the discharge gap, then penetrates into the cathode cavity, and a cathode layer is formed inside the cavity, which leads to the redistribution of the electric field.
The results of our experimental study of the formation dynamics of optical irradiation and populations of metastable levels of neon atoms are in good agreement with the results of numerical simulation. It was experimentally established that in the investigated discharge with a hollow cathode in neon, the concentration of excited atoms at metastable levels reaches a value comparable to the electron density in the discharge, which points to high radiative properties of this discharge.

Acknowledgments
This work was partially supported by a grant from the Russian Foundation for Basic Research No. 19-32-90179 and the project of the Ministry of Education and Science of Russia No. FZNZ-2020-0002.

References
[1] Rauf S, Balakrishna A, Agarwal A, Dorf L, Collins K, Boris D R and Walton S G 2017 Plasma Sources Sci. Technol. 26 065006
[2] Dorf L, Wang J-C, Rauf S, Monroy G A, Zhang Y, Agarwal A, Kenney J, Ramaswamy K and Collins K 2017 J. Phys. D: Appl. Phys. 50 274003
[3] Agarwal A, Bera K, Kenney J, Likhanskii A and Rauf S 2017 J. Phys. D: Appl. Phys. 50 424001
[4] Gazovy’e i Plazmenny’e Lazery’ 2005, ed S I Yakovlenko (Moscow: Nauka) p 820
[5] Ivanov V A, Petrovskaya A S and Skoblo Y E 2013 Optics and Spectroscopy 114 pp 688-95
[6] Golubovskii Yu B, Skoblo A Yu, Kozakov R V and Nekuchaev V O 2008 J. of Phys. D: Applied Phys. 41 105205
[7] Ashurbekov N A and Iminov K O 2016 Generation of High-Energy Electrons in the Nanosecond Gas Discharges with a Hollow Cathode Generation of Runaway Electron Beams and X-Rays in High Pressure Gases vol 1, ed V F Tarasenko (New York: Nova Publishers) p 421
[8] Ashurbekov N A, Iminov K O, Kobzeva V S and Kobzev O V 2010 Tech. Phys. 55 p 1138
[9] Fizicheskie Velichiny 1991, ed N S Grigor’eva and E Z Mejlihova (Moscow: Jenergoatomizdat) p 1232
[10] Tsendin L D 2010 Physics-Uspekhi 53 pp 133-57
[11] Spektroskopiya Gazorazryadnoj Plazmy’ 1970, ed. S E Frish (Leningrad: Nauka) p 359
[12] Ashurbekov N A, Iminov K O, Kobzeva V S and Kobzev O V 2007 Technical Physics Letters 33 pp 517-20
[13] Biberman L M, Vorobiev V S and Yakubov I T 1982 Kinetika Neravnovesnoj Nizkotemperaturnoj Plazmy’ (Moscow: Nauka) p 376
[14] Ashurbekov N A, Iminov K O, Zakaryaeva M Z, Ramazanov A R and Shakhsinov G Sh 2019 J. Phys.: Conf. Ser. 1393 012001
[15] Ashurbekov N A, Iminov K O, Kobzeva V S and Kobzev O V 2009 Russian Physics J. 52 pp 430-6