Parameters of REP DD's plasma formed during the pulse and pulse-periodic modes in dense gases

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ABSTRACT

Main parameters of plasma formed during the pulse and pulse-periodic runaway electron preionized diffuse discharge (REP DD) in argon, nitrogen and air at high pressure were measured. An electron concentration in the plasma of pulse and pulse-periodic REP DD in the elevated pressure argon was determined. Average for pulse value of electron density in the argon plasma of pulse REP DD was $\sim 3\cdot10^{15}$ cm^{-3}. Dynamics of electron density in the atmospheric-pressure plasma of the argon during the REP DD was determined. Measured average values of an electron concentration in the plasma of the pulse-periodic REP DD in atmospheric-pressure air and nitrogen were $\sim 3\cdot10^{14}$ and $\sim 4\cdot10^{14}$ cm^{-3}, respectively. In addition, for the plasma formed during the pulse-periodic REP DD in atmospheric-pressure nitrogen and air average values of an electron temperature and reduced electric field, as well their dynamics were determined. Average value of an electron temperature during the pulse duration for nitrogen and air plasmas was ~ 2 eV. Dynamics of an electron temperature and reduced electric field strength was registered. Data on rotational and gas temperatures in the discharge plasma of atmospheric-pressure nitrogen formed in pulse ($T_r \approx 350$ K, $T_g \approx 380$ K) and pulse-periodic ($T_r \approx 750$ K, $T_g \approx 820$ K) modes were obtained. In addition, measured value of vibrational temperature in REP DD's plasma formed in pulse mode in nitrogen at pressure of 1 bar was $T_v \approx 3000$ K.

Keywords: REP DD, runaway electrons, diffuse discharge, plasma parameters, electron concentration, electron temperature, reduced electric field, Stark's broadening

1. INTRODUCTION

Nonequilibrium low-temperature gas discharge plasma (diffuse plasma) formed at elevated pressure (atmospheric and higher) has great potential of its practical application as the basis of technical devices and/or technological processes [1, 2]. Therefore, such plasma object attracts a lot of attention of both researchers and industrialists (business). Nevertheless, formation of diffuse plasma at high pressure of gases and their mixtures is complex task. It is due to discharge constriction at the increasing of gas medium pressure as in the case of stationary glow discharge [3] and/or volume discharge with additional preionization [4].

It is known about possibility of realization of diffuse discharge at high pressure of gases and their mixtures with no using additional sources of the ionization radiation. The first mention of this discharge relates to the paper [5]. Now it is called REP DD (Runaway Electrons Preionized Diffuse Discharge) [6]. In this case, intensive preionization of discharge gap occurred due to generation of runaway electrons and bremsstrahlung under conditions of REP DD ignition. The most often used way of REP DD formation is applying of voltage pulse with high rate of its value growth (10^{14}-10^{15} V·s^{-1}) to the gap filled with gas under high pressure (atmospheric or higher) where potential electrode has a small radius of curvature (tens-hundreds μm, geometry "point-plane"). Unique features of this type of discharge in dense gases are diffuse form of burning during whole pulse duration, including heavy rare gases (Ar, Kr, Xe) [7], and high specific power of excitation (up to ~ 1 GW·cm^{-3}) [8]. These features indicate that plasma of REP DD has huge potential of its practical application in devices (for example, sources of spontaneous and induced optical radiation with high pulse power) and technologies (for example, cleaning and modification of surface of various materials). Therefore, in recent years a great attention of researches is given to investigation of REP DD. However, directions of investigations were related to conditions of REP DD formation, properties and mechanism of generation of runaway electron beam and bremsstrahlung, mainly ([6], [9] and references there). Since early 2000 one focuses on the study of optical characteristics of REP DD plasma [7, 8, 10-12].

Commonly, the investigation of gas discharge plasma associated with solving of fundamental problem – determination of its main parameters such as electron concentration N_e, electron temperature T_e, gas temperature T_g, vibrational T_v and rotational T_r temperature (for molecular gas), as well reduced electric field strength E/N (E – electric field strength

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[V·cm^{-1}], N – gas density [cm^{-3}]). As far as diagnostics of the REP DD plasma is concerned, there are very few papers [13-17] devoted this problem in the literature. Nevertheless, data on main plasma parameters are very important for the both science (development of theory of the REP DD phenomenon) and practice (definition of the REP DD plasma possibilities).

So, the main objective of this paper is determination of main parameters of plasma of the REP DD formed in dense gaseous mediums during the pulse and pulse-periodic modes.

2. EXPERIMENTAL SETUP AND METHODS

Technique

Experiments were carried out on setup presented on Fig. 1. It was consisted of gas pumping system (*1*), pulser (*2*), driving generator (*3*), discharge chamber (*4*), lenses (*5*), monochromators (*6*, *7*), CCD-camera (*8*), photomultiplier tube (*9*), photomultiplier tube (*10*), digital oscilloscope (*11*), spectrometers (*12*, *13*) and personal computer (*14*).

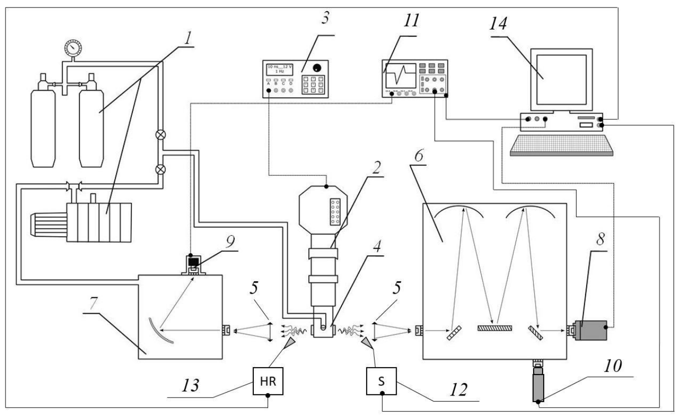

Figure 1. Schematic of experimental setup. *1* – gas pumping system; *2* – pulser; *3* – driving generator BNC-565; *4* – discharge chamber; *5* – lenses; *6* – monochromator MDR-23 LOMO; *7* – vacuum monochromator VM-502; *8* – CCD-camera PI-MAX 2; *9* – photomultiplier tube EMI-9781B; *10* – photomultiplier tube PMT-100; *11* – digital oscilloscope; *12* – spectrometer EPP2000C-25 (StellarNet Inc.); *13* – spectrometer HR-4000 (OceanOptics Inc.); *14* – personal computer.

Gas pumping system (*1*) included gas cylinders, metal pipelines and pressure probes, which allowed to control pressure of gases in the range from fractions-thousands mbar. Gases were helium, argon, hydrogen, nitrogen and air. This system was connected via pipelines with metallic discharge chamber (*4*).

Discharge formation in the present work was in pulse (P-mode) and pulse-periodic (PP-mode) modes. For excitation of gaseous medium two pulsers were used. First was the RADAN-220 (Pulser I) [18], which formed voltage pulses of positive and negative polarity with an amplitude at the high-resistance load of ~ 220 kV, duration at the matched load of 2 ns and risetime in the transmission line of ~ 0.5 ns. Continuous operation of the Pulser I with the frequency $f = 1$ Hz (P-mode) was provided with the driving generator BNC-565 (*3*). Another pulser was the FPG-60 (Pulser II) [19]. The Pulser II formed voltage pulses of negative polarity at the high-resistance load of ~ 50 kV, duration at the matched load of (4-5) ns and risetime in the transmission line of (2-3) ns. Pulser II was operated with pulse repetition rate $f = 2$ kHz (PP-mode). Discharge formation was studied at the negative polarity of voltage pulses only. Ignition of discharge in the P-mode realized in the discharge chamber (Chamber I) presented on Fig. 2, a. The Chamber I was made of stainless steel and had cylindrical form with diameter of 56 mm. Electrodes in the Chamber I were flat grounded aluminum plate (anode) (*4* on Fig. 2, a) and metallic cylinder (*3* on Fig. 2, a) (cathode with small radius of curvature) with diameter of 6 mm made of 100-μm-thick stainless steel. By using of the cathode with small radius of curvature a sharply nonuniform electric field strength distribution in the gap was provided promoting intensive emission of electrons from the cathode surface and their acceleration required for gap preionization and burning of discharge in diffuse form. Interelectrode distance d was 10-16 mm. A diffuse discharge in PP-mode was ignited in the Chamber II (Fig. 2, b) via Pulser II. Electrodes in the Chamber II were potential cathode with length of 40 cm made of sewing needles arranged in a row (*16* on Fig. 2, b) and grounded flat steel anode (*17* on Fig. 2, b). In this case, plasma was formed at atmospheric pressure in the 6 mm interelectrode gap. To avoid discharge constriction due to gas heating in the interelectrode area (in PP-mode) cooling system for its circulation in the chamber was used.

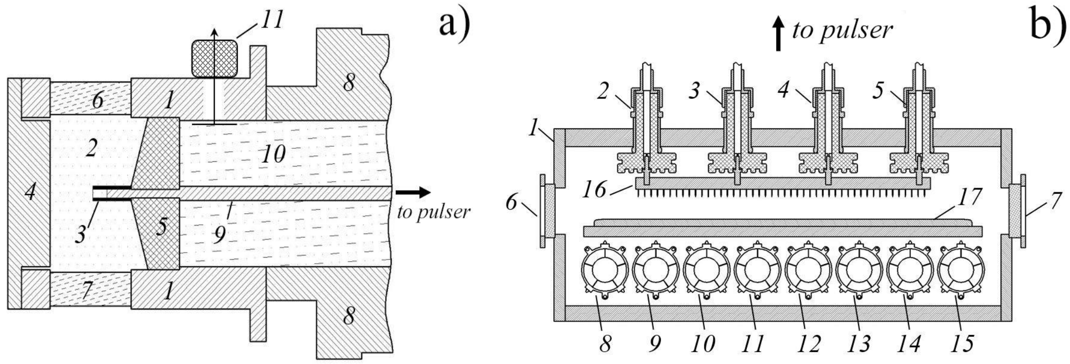

Figure 2. Discharge chamber for REP DD ignition in: a) P-mode. *1* – chamber housing; *2* – gas medium; *3* – potential cathode with a small radius of curvature (steel tube); *4* – grounded flat anode; *5* – insulator; *6, 7* – output quartz windows; *8* – transmission line of the RADAN-220; *9* – high-voltage input; *10* – transformer oil; *11* – capacitive voltage divider. b) PP-mode. *1* – chamber housing; *2-5* – high-voltage inputs; *6, 7* – output quartz windows; *8-15* – cooling system; *16* – potential cathode (row with length of 40 cm of sewing metallic needles); *17* – grounded flat steel anode.

Plasma radiation from the discharge chambers was brought out via the side quartz windows (*6*, *7* on Fig. 2, a and b). Image of discharge plasma was rendered with lenses (*5*) in the plane of inlet slits of monochromators MDR-23 LOMO (*6*) and VM-502 (Acton Research Inc.) (*7*).

Input slit of MDR-23 had a rectangular shape (instead standard oval-shape slit) with normal width of 30 μm (used in experiments). Diffraction grating of the MDR-23 had 1200 grating grooves per mm. The value of a reciprocal linear dispersion of this monochromator was 1.3 $nm\cdot mm^{-1}$. The range of spectral sensitivity is 200-1000 nm. For registration of an optical signal, passed monochromator, instead of the output slit the CCD-camera PI-MAX 2 (Princeton Instruments) (*8*) was mounted. An optical signal was registered with this camera during a P-mode. The range of spectral sensitivity of the CCD is 180-900 nm. Dynamic range is 65536:1. The size of the camera matrix was 1024×1024 px (13×13 mm). Horizontal axis of the matrix corresponded to direction of the dispersion. In additional, photomultiplier tube PMT-100 (*10*) was mounted at the second output slit of MDR-23 for registration of time behavior of radiation intensity.

Slits of the monochromator VM-502 were rectangular too. In experiments their width was 30 μm (normal width is 20 μm). The reciprocal linear dispersion of the VM-502 is equal to 4 $nm\cdot mm^{-1}$. Used this monochromator it was possible to register an optical radiation in the spectral range 120-540 nm. The monochromator was equipped with a photomultiplier tube EMI9781B (*9*). This PMT can reliably registered signals with rise time ~ 3 and fall time ~ 30 ns.

For the both monochromators at the indicated slit widths by measuring the full width at half-maximum (FWHM) of the mercury atomic line (Hg I, $\lambda = 435.8$ nm) an instrumental function $\Delta\lambda_{instr}$ was determined. Its value was up to ~ 0.24 Å for the MDR-23 and ~ 3 Å for the VM-502.

Waveforms of voltage pulses were registered with capacitive voltage divider. For registration of discharge current waveforms the shunt ($R_{sh} \sim 0.04\ \Omega$) made of thin-film low inductance chip-resistors was used. Electrical signals from capacitive divider, current shunt and probes of optical radiation were registered with digital oscilloscopes (*11*) DPO 70604 ($B_w = 6$ GHz) and TDS 3054B ($B_w = 0.5$ GHz). Overall spectrum of optical radiation of the discharge plasma in the range 200-850 nm was registered with a spectrometer EPP2000C-25 (StellarNet Inc.) (*12*). As well, radiation spectrum in the range 330-420 nm can be registered with a spectrometer HR-4000 (Ocean Optics Inc.) (*13*).A value of FWHM of instrumental function $\Delta\lambda_{instr}$ of these spectrometers was ~ 8 Å and ~ 1.5 Å, respectively. Integral images of discharge plasma glowing were taken with a digital camera SONY A100. Experimental data storage and their processing were performed with personal computer (*14*).

Methods

For determination of main parameters of plasma of the REP DD formed during the pulse and pulse-periodic modes in high-pressure gases methods of optical emission spectroscopy were applied. This is explained by relative simplicity of experiment conducting and used measuring technique. Besides these methods are contactless, that is they don't perturb the plasma.

N_e measurements

For the N_e measurements in the present work two methods were used. First way is the method based on measurement of FWHM $\Delta\lambda_{1/2}$ of spectral lines broadened due to linear Stark's effect. According to this method, relations between electron density gas discharge plasma and spectral line's FWHM is expressed by the formula (1) [20]:

$$\Delta\lambda_{1/2} = 8.16 \cdot 10^{-19} \cdot \lambda_0^2 \cdot (1 - 0.7 N_D^{-1/3}) \cdot (n_2^2 - n_1^2) \cdot (\frac{Z_p^{1/3}}{Z_e}) \cdot N_e^{2/3} . \quad (1)$$

In formula (1): $\Delta\lambda_{1/2}$ – the true value of FWHM of the spectral line defined as difference between half-width of experimental line's profile $\Delta\lambda_{exp}$ and instrumental function value $\Delta\lambda_{instr}$; λ_0 – the value of the central wavelength; n_1, n_2 – principal quantum numbers of lower and upper states of transitions; N_D – the number of particles in the Debye sphere; Z_p – ion charge multiplicity; Z_e – atomic number; N_e – electron concentration. The values of broadening of the atomic hydrogen lines H_α (λ = 656.3 nm) and H_β (λ = 486.1 nm) for determination of N_e in the REP DD plasma were used in experiments. In this case, a small admixture (~ 3 mbar) of hydrogen H_2 was added to main gas. Reliability of this method is ~ 30 % for the N_e in the range 10^{14}-10^{18} cm^{-3}.

The second method for N_e estimation was a one based on known relation (2), which can be converted in (3):

$$I_{dis} = j_{dis} S = e N_e v_d S , \quad (2)$$

$$N_e = (\frac{1}{e \mu_e S}) \frac{d}{R_p} . \quad (3)$$

In expressions (2), (3): I_{dis} – amplitude value of discharge current; j_{dis} – density of discharge current; S – cross-section of current-flow zone; e – electron's charge; N_e – electron concentration; v_d – drift velocity of an electrons; μ_e – electrons mobility; d – interelectrode distance; R_p – plasma's resistance So, finding the R_p using the waveforms of discharge current obtained during the experiments a value of N_e in the discharge plasma can be estimated (more details in [17]). Using of this method in the present work was caused by insufficient for registration intensity of hydrogen atomic lines.

T_e and E/N measurements

For measurement of an electron temperature and reduced electric field in the diffuse plasma of the high-pressure REP DD the method based on radiative-collisional plasma's model was used. According to this method values of T_e and *E/N* in gas plasma are related with ratio $R_{391/394}$ of values of peak intensities of the ionic N_2^+ (λ = 391.4 nm) and molecular N_2 (λ = 394.3 nm) nitrogen bands, so called first negative ((1$^-$)-system, transition $B^2\Sigma_u^+ \rightarrow X^2\Sigma_g^+$) and second positive ((2$^+$)-system, transition $C^3\Pi_u \rightarrow B^3\Pi_g$) systems of nitrogen molecule [21]. Dependencies of $R_{391/394}$ from T_e [22] and *E/N* [23] are presented on Fig. 3. So, by measuring of peak intensity values of nitrogen bands indicated above one can determine electron temperature and reduced electric field in the discharge plasma.

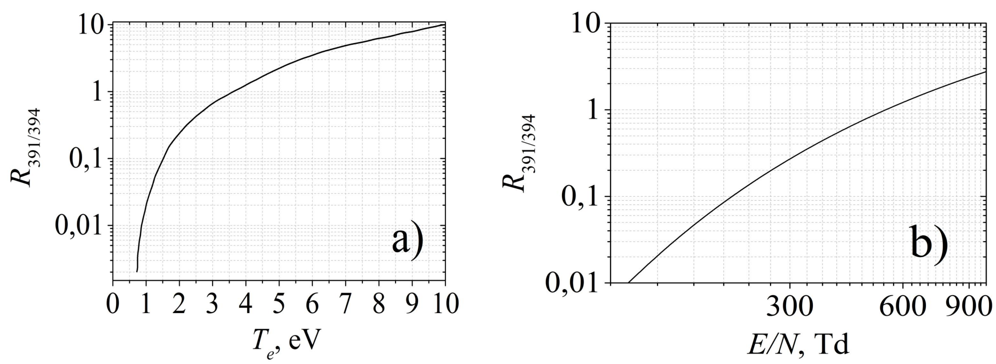

Figure 3. Ratio $R_{391/394}$ of values of peak intensities of the ionic N_2^+ (λ = 391.4 nm) and molecular N_2 (λ = 394.3 nm) nitrogen bands as function of electron temperature T_e (a) [22] and reduced electric field *E/N* (b) [23]. 1 Td = 10^{-17}V·cm^2.

However, to use this method fulfillment of two conditions is required. These are:

I. Electron energy distribution function in the discharge plasma must have Maxwellian view;

II. Excitation of upper states of the transitions $B^2\Sigma_u^+$ (1$^-$) and $C^3\Pi_u$ (2$^+$) is due to direct electron impact from ground state $X^1\Sigma_g^+$ of the nitrogen molecule mainly.

Earlier [17], it was shown that conditions I and II indicated above are fulfilled for plasma of the REP DD in nitrogen of atmospheric pressure and method for measurement of T_e and E/N can be used during the ~ 10 ns after beginning of discharge current.

T_v, T_r and T_g measurements

In this paper values of T_v, T_r and T_g were determined for the REP DD plasma in the atmospheric-pressure nitrogen. For measurement of these parameters the radiation of the (2$^+$)-system was used.

It is known [24], there is simple relation between T_v, and T_r in $X^1\Sigma_g^+$ and $C^3\Pi_u$ states when excitation of $C^3\Pi_u$ state of the nitrogen molecule occurs due to direct electron impact from ground state $X^1\Sigma_g^+$ (it is fulfilled for plasma REP DD in nitrogen at pressure 1 bar). Wherein, if *RT*-relaxation in $X^1\Sigma_g^+$ (equilibrium between translational and rotational degrees of freedom) state is fast, that excitation of $C^3\Pi_u$ state by direct electron impact from the ground state result in copying of rotational distribution of the $X^1\Sigma_g^+$ state. Thus, T_r can be determined by plotting of Boltzmann graph for unresolved part of spectral energy distribution of the vibrational-collisional band $v' = 0 \rightarrow v'' = 0$ ($\lambda = 337.1$ nm) corresponded to transitions between rotational energy levels [25]. So, knowing the T_r a temperature of heavy particles T_g (gas temperature) can be found by using the expression (4) [24, 26, 27]:

$$T_g = \frac{B^0}{B^*} T_r = 1.09 \cdot T_r, \qquad (4)$$

where B^0 and B^* – a rotational constants of grounded $X^1\Sigma_g^+$ and excited $C^3\Pi_u$ states, respectively.

As far as value of T_v is concerned that it can be measured from determination of inclination angle of Boltzmann graph for following sequences of vibrational-collisional bands: $v' = 0 \rightarrow v'' = 1$ ($\lambda = 357.69$ нм), v' $1 \rightarrow v'' = 2$ ($\lambda = 353.67$ нм), v' $2 \rightarrow v'' = 3$ ($\lambda = 350.05$ нм) and/or $v' = 0 \rightarrow v'' = 2$ ($\lambda = 380.49$ nm), $v' = 1 \rightarrow v'' = 3$ ($\lambda = 375.54$ nm), $v' = 2 \rightarrow v'' = 4$ ($\lambda = 371.05$ nm). It should be pointed out that due to long *VT*-relaxation process vibrational energy distribution in ground and excited states could be differed (rightly for low T_v). However, at the $T_v \sim 3000$ K the difference is not more than ~ 20 %. Difference disappears at higher values of the vibrational temperature (4000-5000 K) [24, 28].

3. EXPERIMENTAL RESULTS AND DISCUSSION

In our previously work [14], first attempt on measuring of main parameters of REP DD's plasma in the dense gas medium were made. There are data on electron concentration in the discharge plasma of helium formed in P-mode in this paper. Dependence of average per pulse value N_e from helium pressure in the range 1-6 bar was obtained. As well, data on behavior of N_e for the both in time and along the longitudinal discharge axis for REP DD plasma of atmospheric-pressure helium are presented in [14]. It should be noted, that results of experiments on determination of N_e in the helium plasma of REP DD in [14] are correlated with ones obtained for similar conditions and published later [15].

Besides [14], it should be mentioned paper [17] where for plasma of REP DD ignited in P-mode in the atmospheric-pressure nitrogen. It is important to say, that in [17] calculations proving the applicability of the method for determination of T_e and E/N in the plasma of REP DD in atmospheric-pressure nitrogen are presented. Thus, there it is shown that to the moment when intensity of ionic and molecular nitrogen bands is sufficiently for registration the Maxwellian electron energy distribution function is realized and excitation of $B^2\Sigma_u^+$ (1$^-$) and $C^3\Pi_u$ (2$^+$) states is due to direct electron impact from ground state $X^1\Sigma_g^+$ predominantly. There are data on electron density N_e, electron temperature T_e and reduced electric field strength E/N in [17]. An average for pulse values of N_e, T_e and E/N in atmospheric-pressure nitrogen plasma formed with frequency of 1 Hz was $\sim 2 \cdot 10^{14}$ cm^{-3}, ~ 2 eV and 240 Td, respectively. In addition, temporal behavior of N_e, T_e and E/N is presented there. Obtained data on dynamics of T_e and E/N are in accordance with theoretical [29] and experimental [16] results of other authors.

In the present paper the following experimental results are presented. For plasma of the REP DD formed in the argon measurements of an electron concentration were carried out. It should be noted, that for determination of N_e in the argon plasma the method of Stark's broadening was used. Typical image of glow of plasma of the REP DD ignited in P-mode in the argon is shown on Fig 4, a. On Fig 4, b dependence of average for pulse value of electron density in the REP DD plasma on argon pressure in the range 0.5-2 bar for the middle of the discharge gap is presented. It is seen, that N_e increases with pressure increasing (as in the helium [14]). In addition, for the plasma of the REP DD in the argon formed in P-mode values of an electron concentration in various cross-sections along the longitudinal axis of the discharge gap were measured. Similar to the case with helium [14], as one moves from the potential cathode toward flat anode reducing of N_e is observed (from $\sim 3{\cdot}10^{15}$ cm^{-3} to $\sim 1.5{\cdot}10^{15}$ cm^{-3}). This behavior of an electron density along the gap can be explained by change in the discharge geometry (increasing of current-flow zone away from the electrode with a small radius of curvature).

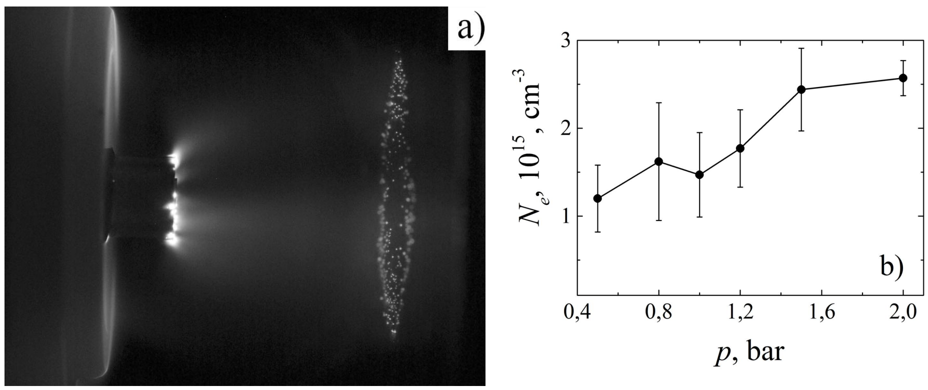

Figure 4. a) Integral image of glow of plasma of the pulsed REP DD in the atmospheric-pressure argon. b) Dependence of average value of N_e in the diffuse argon plasma on gas pressure. P-mode, f = 1 Hz. Tubular potential cathode. Flat grounded Al-anode. Interelectrode distance 12 mm.

On the Fig. 5, a integral image of glow of plasma formed by REP DD ignited in PP-mode in the argon of atmospheric pressure is presented. As it is seen from photo, discharge has form of diffuse jets originating from each needle. A value of N_e in the argon plasma was determined by the measuring of Stark's broadening of hydrogen atomic line H_α. On the Fig. 5, b (curve *4*) temporal behavior of an electron density in atmospheric-pressure argon plasma formed in PP-mode for the middle of the gap is presented. According to obtained dependence a value of N_e achieved its maximum $\sim 2{\cdot}10^{16}$ cm^{-3} in the instance corresponding to the maximum of discharge current I_{dis} (curve *2* on Fig. 5, b). After that, there is a monotonic decline of an electron concentration in the gap. An average value of N_e was $\sim 5{\cdot}10^{15}$ cm^{-3}. It should be pointed out, that view of time dependence of an electron concentration (curve *4* on Fig. 5, b) can be explained by voltage pulse modulation due to its reflection from pulser (resistance of transmission line is not in accord with pulser's one).

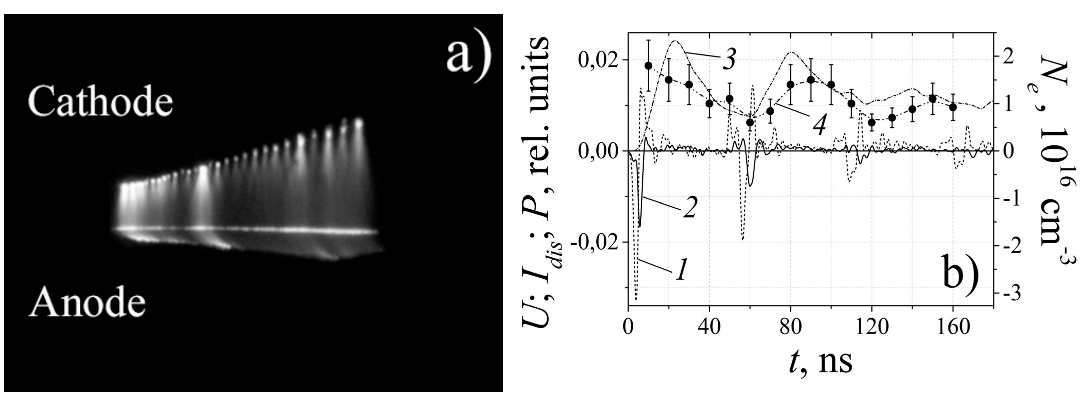

Figure 5. a) Integral image of glow of plasma of pulse-periodic REP DD in the argon. b) *1* – waveform of voltage pulse U; *2* – waveform of discharge current pulse I_{dis}; *3* – time dependence of radiation intensity P of hydrogen line H_α; *4* – temporal behavior of N_e in the argon plasma. Argon, 1 bar. PP-mode, f = 2 kHz. Potential cathode with length of 40 cm (row of needles). Flat grounded anode. Interelectrode distance 6 mm.

For similar excitation conditions data on electron concentration in the discharge plasma were obtained for REP DD ignited in PP-mode in nitrogen and air at pressure of 1 bar. Integral images of glow of the REP DD plasma of atmospheric-pressure nitrogen and air are presented on Fig. 6. So as, radiation intensity of hydrogen lines H_α and H_β from discharge plasma of nitrogen and air was insufficient for registration that for estimation of an electron density relation (3) was used. The maximal values of an electron concentration in the middle of gap corresponding to moment when discharge current achieved its maximum were $\sim 4 \cdot 10^{14}$ cm^{-3} for nitrogen and $\sim 3 \cdot 10^{14}$ cm^{-3} for air.

Besides the N_e, for the diffuse atmospheric-pressure plasma of nitrogen and air formed in pulse-periodic mode values of electron temperature T_e and reduced electric field *E/N* were measured. Average values of T_e and *E/N* for nitrogen and air were ~ 2 eV, ~ 270 Td and ~ 1.8 eV, ~ 260 Td, respectively. These values are correspond to ratio of peak intensities of ionic N_2^+ and molecular N_2 nitrogen bands is equal to $R_{391/394} \sim 0.3$.

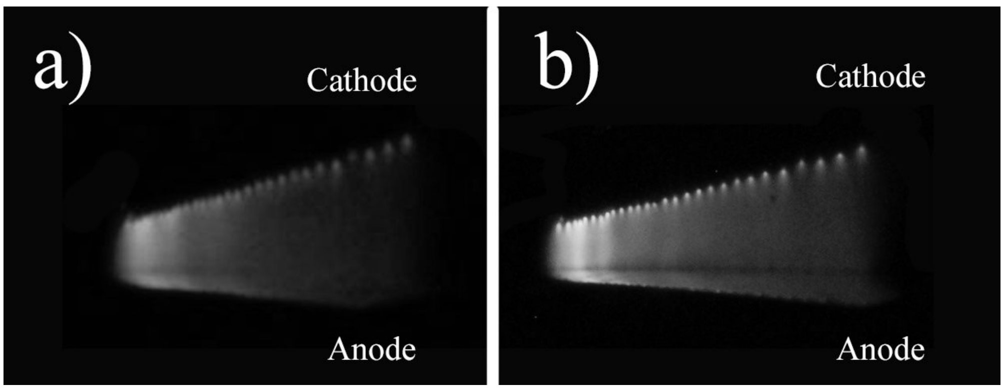

Figure 6. Integral images of glow of plasma of the REP DD in atmospheric-pressure nitrogen (a) and air (b). PP-mode, *f* = 2 kHz. Potential cathode with length of 40 cm (row of needles). Flat grounded anode. Interelectrode distance 6 mm.

In addition, time dependencies of radiation intensity of ionic N_2^+ (λ = 391.4 nm) and molecular N_2 (λ = 394.3 nm) were registered. It allowed to determine the time behavior of ration $R_{391/394}$ and dynamics of values of T_e and *E/N*. It was found, that during the ~ 10 ns after beginning of discharge current (when method allows to obtain reliable results) decreasing of electron temperature and reduced electric field strength in the middle of discharge gap occurred: from ~ 3.5 eV and ~ 450 Td to ~ 2 eV and ~ 270 Td (for nitrogen plasma) and from ~ 3 eV and ~ 400 Td to ~ 2 eV and ~ 260 Td (for air plasma). That is values of T_e and *E/N* for the plasma of REP DD in atmospheric-pressure nitrogen and air reduce in 1.7 and 1.5 times, respectively. It corresponds to the following ratio $R_{391/394}$ dynamics: 0.6 → 0.3 (N_2) and 0.55 → 0.3 (air). It can be assumed, that in the near-cathode area a higher values of an electron temperature and reduced electric field strength are realized.

It is important to note, that obtained in our experiments data on T_e and *E/N* are correlated with ones obtained due to calculations performed for similar excitation conditions [16].

As well, for plasma of REP DD in the nitrogen at pressure of 1 bar ignited in P- and PP-modes values of rotational and gas temperatures was measured. For determination of T_r and T_g the Boltzmann graph for unresolved part of spectrum corresponding to rotational transitions of vibrational-collisional band of (2^+)-system of the nitrogen molecule (Fig. 7, a (curve *1*) and Fig. 7, b) was plotted. Then finding the inclination angle of this graph value of T_r can be founded. Knowing T_r and using (4) T_g calculated. It should be pointed out that using of this method for measuring of T_r and T_g is explained by excitation of $C^3\Pi_u$ state due to direct electron impact from ground state (proved in [17]) and fast *RT*-relaxation. Actually, according to [25] average number of inelastic collisions between N_2 molecules required for the exchange of translational and rotational energy (relaxation) is 4-6. An average time between collisions τ_{coll} can be calculated with expression (5) [3]:

$$\tau_{coll} = \frac{1}{[N_2] \cdot \sqrt{2} \cdot \sigma \cdot v_T}, \qquad (5)$$

where $[N_2]$, v_T, σ – concentration, thermal velocity and gas-kinetic cross section of nitrogen molecules. Since estimated τ_{coll} and *RT*-relaxation time for the room temperature nitrogen was 0.13 and 0.65 ns, respectively. So, the relaxation time is more than order of magnitude less than the duration of REP DD under study.

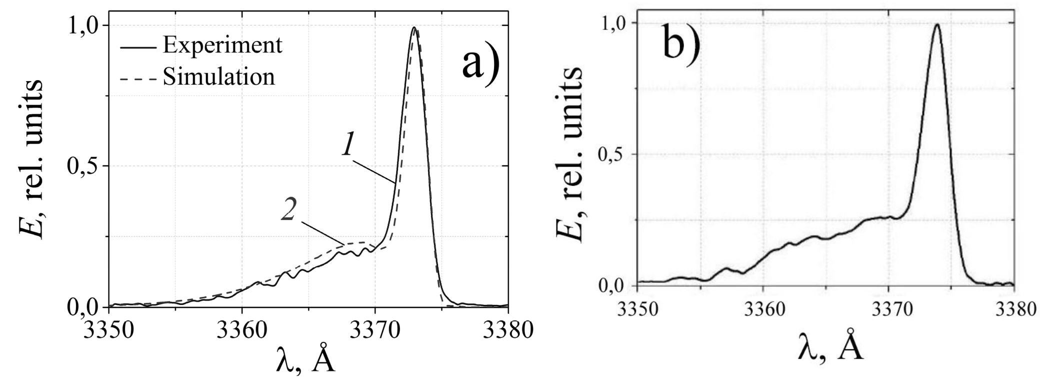

Figure 7. a) Experimental (*1*) and theoretical (*2*) (SPECAIR [30] simulation) spectral energy distribution in vibrational-collisional band $0 \rightarrow 0$ ($\lambda = 337.1$ nm) of N_2. P-mode. b) Experimental spectral energy distribution in vibrational-collisional band $0 \rightarrow 0$ ($\lambda = 337.1$ nm) of N_2. PP-mode. Pressure 1 bar.

Measured values of T_r and T_g in the plasma of pulse and pulse-periodic REP DD in atmospheric-pressure nitrogen was 350 and 380 K (P-mode) and 750 and 820 K (PP-mode). These values indicate that REP DD plasma is low-temperature and nonequilibrium.

In addition, plotting the Boltzmann graph for sequence of vibrational-collisional bands of second positive system of nitrogen molecule (Fig. 8) the value of vibrational temperature in the discharge plasma of nitrogen at pressure 1 bar was estimated. This value was $T_v \approx 3000$ K.

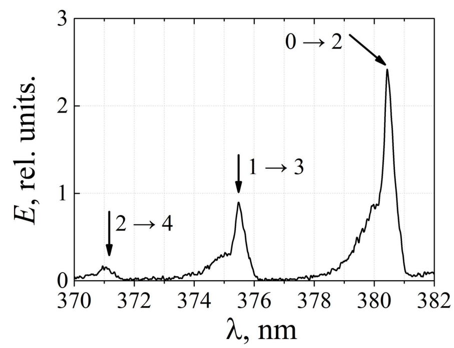

Figure 8. Spectral energy distribution in vibrational-collisional bands $2 \rightarrow 4$, $1 \rightarrow 3$ and $0 \rightarrow 2$ of the second positive system of nitrogen molecule.

Using the determined in experiments values of T_e, T_v, T_r and T_g simulation of profile of the vibrational-collisional N_2-band $0 \rightarrow 0$ ($\lambda = 337.1$ nm) with the code SPECAIR [30] was performed (curve *2* on Fig. 7, a). As it is seen from Fig. 7, a a good conformity between experiment and simulation is observed. So, this fact points on reliability of methods used in work for determination of main parameters of plasma formed during the excitation of dense gaseous mediums by the REP DD.

4. CONCLUSION

In the carried out experiments average values of main parameters (N_e, T_e, T_v, T_r, T_g and E/N) and their time dependence in plasma formed as a result of excitation of dense gases (He, Ar, N_2, air) by runaway electron preionized diffuse discharge ignited in pulse and pulse periodic modes were determined with methods of optical emission spectroscopy. Measured values of an electron concentration N_e belonging to the range 10^{14}-10^{16} cm^{-3} indicate that this plasma is dense. As far as electron, vibrational, rotational and gas temperatures are concerned that relation between their values measured for REP DD plasma satisfies the expression (6) [31]:

$$T_e >> T_v >> T_r \approx T_g \,. \tag{6}$$

It allows to state that REP DD plasma is a dense low-temperature nonequilibrium.

In addition, it can be assumed that data on main parameters of the pulsed and pulsed-periodic REP DD's plasma of dense gases will be useful in future for the both science and practice. So, for example, these values can be used for modeling of processes in plasma results of which will supplement theory of REP DD phenomenon and will help reveal possibilities of practical application of this plasma object as a basis of devices and technologies.

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