MATERIALS. TECHNOLOGIES. DESIGN

УДК 621.373.13
P.A.C.S. 52.38.Dx

DOI 10.54708/26587572_2023_5212185

APPLICATION OF LASER RADIATION FOR CONTROL OF RADAN COMPACT PULSE GENERATOR

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ABSTRACT

This paper presents the results of experimental and theoretical investigations of a plasma jet formed by YAG: Nd^{3+} laser radiation on an anode in a high-voltage gas gap. Conditions corresponding to the minimal instability of 0.3 ns and delay were experimentally found. The physical mechanisms determining the delay of the gas gap overlap by the plasma jet and the obtained instability level are discussed. A model of processes occurring on the ionization wavefront determined by the absorption/excitation of gas atoms and by the effects of a high-field domain was proposed.

KEYWORDS

Plasma jet dynamics; high-voltage gas gap.

ПРИМЕНЕНИЕ ЛАЗЕРНОГО ИЗЛУЧЕНИЯ ДЛЯ УПРАВЛЕНИЯ КОМПАКТНЫМ ГЕНЕРАТОРОМ ИМПУЛЬСОВ РАДАН

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АННОТАЦИЯ

В работе представлены результаты экспериментальных и теоретических исследований плазмы, формируемой излучением YAG: Nd^{3+} лазера на аноде в высоковольтном газовом разряднике. Экспериментально найдены условия, соответствующие минимальной нестабильности 0,3 нс и задержке. Обсуждаются физические механизмы, определяющие задержку перекрытия газового разрядника плазмой и получаемый уровень неустойчивости. Предложена модель процессов, происходящих на фронте волны ионизации, обусловленных поглощением и/или возбуждением атомов газа и воздействием области усиления поля.

КЛЮЧЕВЫЕ СЛОВА
Динамика плазменной струи; высоковольтный газовый разрядник.

Introduction

Laser-induced gas breakdown [1] is widely used in high-pressure gas gaps with optical control [2, 3]. The stability of the delay of the switch transition to the conducting state is important both for decreasing commutation losses to decrease and when it is necessary to simultaneously fire up several devices operating on a conjoint load. This transition is governed by physical processes occurring in the discharge gap that overlap by the plasma jet. Despite decades of development, this issue determines the trends for developing such devices even now. Therefore, studies aimed at their development are curried out, for example, new optically controlled switches have been patented quite recently [4]. From a fundamental point of view, a study of plasma jet behaviour in the electric field is also an opportunity to better understand streamer physics, especially its dynamics [5], from its initiation to gas gap overlap. The point is that some experimental data [6] cannot be explained in the frameworks of existing theoretical models [7]. Moreover, one can easily estimate the mean velocity of the ionization wave traveling across the gas gap. It had an order of magnitude of 10^6 m/s. The estimates obtained cannot be described by the well-known laser-supported detonation wave (LSD) model [8] because the velocity of the LSD does not exceed 10^4 m/s under similar conditions [9]. At the same time, in one of the latest reviews [5], there is practically no information about models of plasma jet behaviour in an electric field in a gaseous medium at pressures higher than 1 MPa. The case corresponding to the change in plasma density from the metal density to 10^{20} cm^{-3} was also not considered. However, it has been shown that the presence and expansion of quasi-neutral dense plasma provided an electric field gain in front of the ionization wave [10]. Therefore, the main objective of this paper is to create a simple physical and mathematical model of high-voltage discharge initiated by laser radiation in a high-density gaseous medium.

1. Apparatus and experimental results

The main problem with the standard ignition of the RADAN accelerator using a thyratron is the presence of microsecond jitter. Fig. 1 shows the dependence of switch-on delay the primary switch t_s of such accelerator on pressure P when gas gap operates in self-breakdown mode.

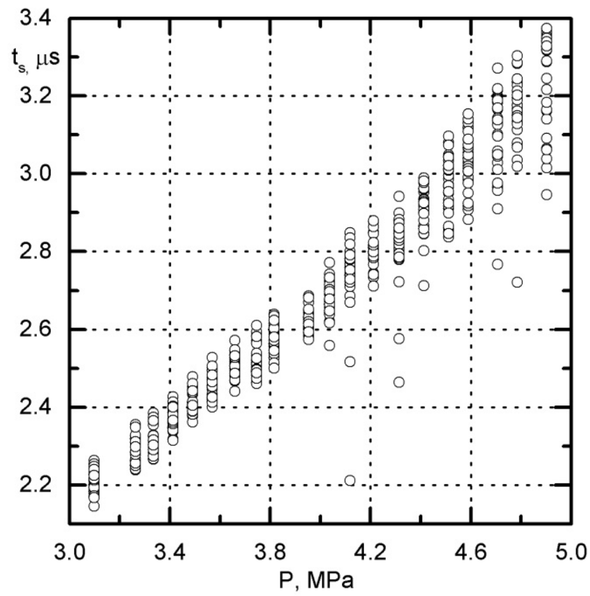

Fig. 1. Dependence of switch-on delay of gas gap operating in self-breakdown mode on pressure

Рис. 1. Зависимость от давления задержки включения разрядника в режиме самопробоя

Fig. 2 shows the dependence of calculated Δt of the accelerator switch-on jitter (1) on pressure P operating in self-breakdown mode. Also similar relation is used to calculate jitter for gas gap operating in laser controlled mode.

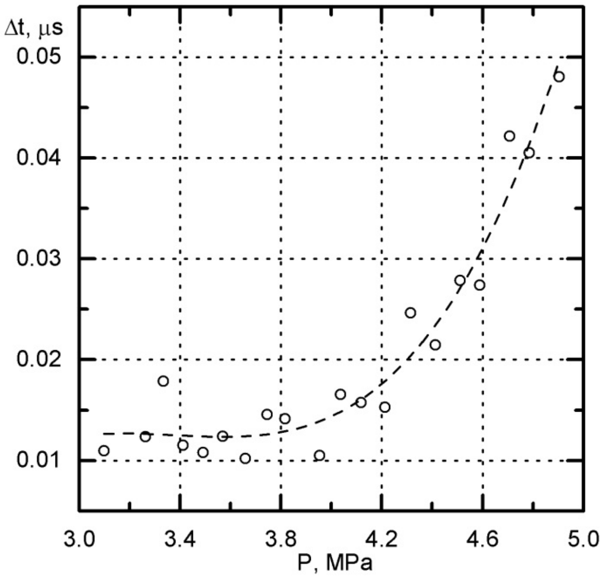

Fig. 2. Dependence of the jitter switch-on delay operating in self-breakdown mode on pressure

Рис. 2. Зависимость от давления джиттера включения при работе в режиме самопробоя

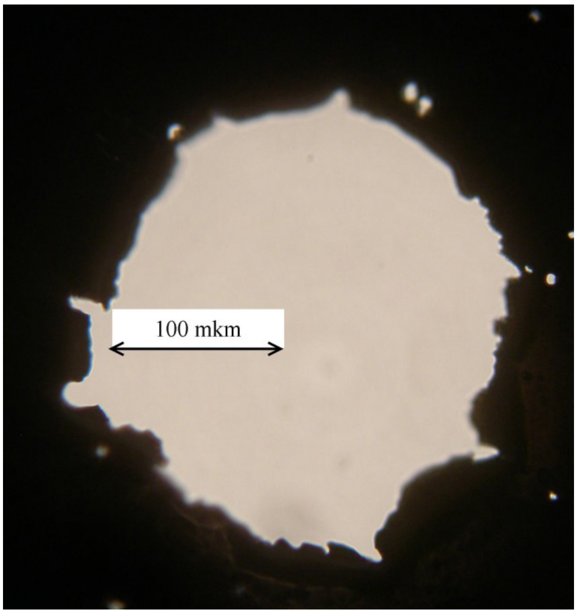

Fig. 3. Laser focusing spot on anode electrode

Рис. 3. Пятно фокусировки лазера на анодном электроде

$$\Delta t = k_S \cdot \sqrt{\frac{\sum_{i=1}^{N}\left(t_i - t_m\right)^2}{N \cdot \left(N-1\right)}}, \quad (1)$$

here t_m is mean switch-on delay, N is number of shots. We used 30 shots set for each pressure we investigated. It is clear that direct use for the study of nanosecond processes in this case seems to be impossible. This problem can be overcome by using laser radiation to ignite the plasma in the spark gap [2, 3]. For this purpose we used Q-switched YAG: Nd^{3+} LS 2134 laser pulses having energy of 200±0.5 mJ, FWHM=14 ns, and wavelength λ =1064 nm to form plasma on anode electrode. The focused laser radiation spot had a radius about $R_f=10^{-4}$ m, (Fig. 3) and the focal point of the lens was adjusted behind the anode surface to avoid uncontrolled optical breakdown of the gas in the gap of d=3, mm.

The choice of anode for plasma ignition was stipulated by the main objective of the paper present, i.e., to reduce switch trigger delay and to mountain the stability of plasma formation in the discharge gap [11]. We calculated the electric field for the real geometry of the gas gap in the presence and absence of plasma to find its maximal value. For example, for an anode voltage U_a=190 kV and grounded cathode, the calculated electric field undistorted by plasma this maximum had a value of $E_{max}=7.1\times10^7$ V/m. The gas gap can be filled with dry nitrogen at pressure range from 3 to 5 MPa. In the paper we present results of laser ignition for pressure of 4 MPa, which is typical for RADAN devices. The aim was to sustain gas gap overlap conditions similar to those presented in the primary switches of electron beam accelerators [12] or similar devices. One of the distinguishing features of the experimental setup we used was the application of voltage to the gas gap, which increased in the time range of a few microseconds. That is two or three orders of magnitude slower than the typical delay value obtained. Therefore, it was possible to change the voltage of the plasma ignition by a simple shifting of the laser pulse relatively at the beginning of the gas gap voltage rise. This allows one to change the relative gap voltage $\sigma=(U_s-U_b)/U_s$ in a broad range. Here U_b is a laser-controlled switch-on voltage, U_s – gap self-breakdown voltage. The laser controlled breakdown delay t_b relative to the laser pulse beginning was observed experimentally. Fig. 4 presents it in dependence on the voltage σ applied to the gap.

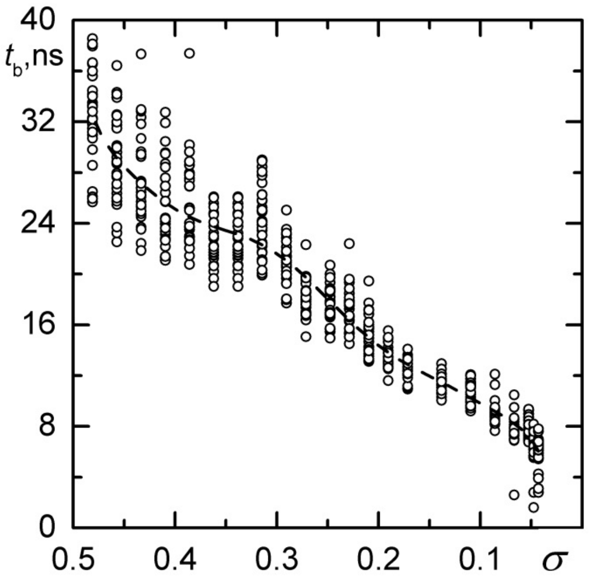

Fig. 4. The dependency of switch-on delay t_b vs relative switch-on voltage σ

Рис. 4. Зависимость задержки включения t_b от относительного напряжения σ

Fig. 5 presents the estimation of the mean velocity of the ionization wave traveling across a gas gap.

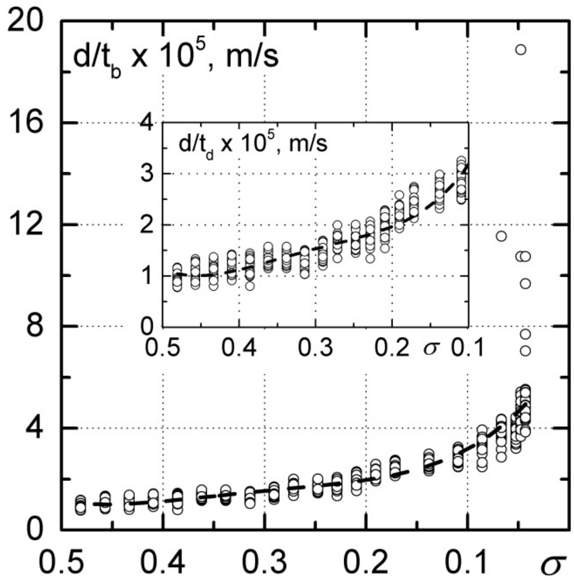

Fig. 5. The dependency of the mean velocity of the ionization wave *vs* relative switch-on voltage σ

Рис. 5. Зависимость средней скорости волны ионизации от относительного напряжения σ

2. Discussion

We can perform the following simple preliminary estimations. The irradiated volume can be assumed as a cylinder with a base equal to the focal spot and a height $h=0.5\cdot\lambda=532$ nm [14], where λ is the wavelength of the laser radiation we used. Therefore, one can estimate the volume $V=\pi R_f 2\cdot h=1.7\cdot10^{-14}$ m^3, which contains about $N_a=1.4\cdot10^{15}$ atoms. For this case, an atom velocity can be estimated: $C_a\approx(W_{pa}/(\gamma-1)\cdot M_a)^{1/2}=4.6\cdot10^4$ m/s, where M_a is the mass of atoms and γ=5/3 is an adiabatic index in the assumption of the neglecting of atom interaction. This velocity determines the overlap time of the gap distance *d* by the plasma $t_b=64.5$ ns. This estimation provided results that are in good agreement with the experimental data [15]. Such estimations give upper bound value.

One can obtain the lower bound estimation assuming an irradiated volume as a sphere with a focus spot radius. Thus, this volume $V=4\pi R_f^3/3$ = $4.2\cdot10^{12}$ m^3 contains $N_a=3.5\cdot10^{17}$ atoms. In this case, each atom can get from the laser pulse only W_{pa}=3.3 eV/atom, i.e. W_{pa}/Λ_i=0.78, here Λ_i is ionization energy of iron, which we used as model material of anode. Obviously, it is not enough for ionization, and the anode material expansion will occur mainly in the form of neutral atoms. The latter cannot lead to the electric field distortion, i.e. formation of a high-field domain (HFD), and as result a significant delay decrease in discharge takes place, as compared with the self-breakdown of discharge gap in the absence of laser triggering (compare Fig. 1 and Fig. 4). It should be noted that this estimation is in poor agreement with our experiment data obtained. The discharge development time, i.e. delay of the breakdown of the gas gap, appears non-linear in dependence on the electric field.

Also, to characterize the delay instability, the confidence interval of the random error for confidence level p=0.95 was calculated. It has a minimal value of 0.3 ns in the range σ=0.1÷0.15. And at last the discharge development velocity $C_a=(2.5\div3.8)\cdot10^5$ m/s for $t_b=(8\div12)$ ns was estimated for this σ, Fig. 5. For smaller values of σ, the instability begins to grow, and its dependence on σ seems to be changing.

The estimates above show the necessity to consider the following:

1) the anode material in the initial state has almost free electronic component, which obeys the Fermi-Dirac statistics;

2) electrons get laser radiation energy only in the process of electron-phonon (electron-ion) interaction and then transfer it to the heavy atom/ion component;

3) the potential of the external electric field is maximum on the anode side $\varphi_a=U(t)$, and as we used a grounded cathode typical for RADAN accelerators, $\varphi_c=0$; therefore, it slows down the electrons and accelerates the ions to the cathode;

4) the velocity of a HFD boundary (front) is in fact the phase velocity weakly related to the transfer of matter. Under the assumption of strong discontinuity, integral conservation laws similar to the integral relations of the detonation wave front (we can say even, the combustion wave front) must be satisfied on the HFD boundary.

For further consideration the approach proposed in [16] is used. Considering the laser pulse FWHM ~10^{-8} s and the settling time of local thermodynamic equilibrium (LTE) (in a metal density plasma, the equilibrium is established for each subsystems at the time ~10^{-13} s, and temperatures of electrons and phonons are equalized in ~$10^{-11}\div10^{-10}$ s [17]), one can limit the process model for the first approximation on the single-fluid, one-temperature approach.

Then, the model equations will be the following:

$$\frac{\partial \rho_a}{\partial t}+\frac{\partial \rho_a v_a}{\partial x}=0 \tag{2}$$

is mass conservation law.

$$\rho_a\left(\frac{\partial v_a}{\partial t}+v_a\frac{\partial v_a}{\partial x}\right)=-\frac{\partial P_a}{\partial x} \tag{3}$$

is motion equation.

$$\frac{\partial j_a}{\partial t}=\frac{e^2\bar{z}_a n}{m}E-\nu_{ea}j_a \tag{4}$$

is generalized Ohm's law.

Here $\rho_a=(M_a+z_{ma}m)n_a$ is the density, n_a – concentration, for iron. And $z_{ma}n_a=n_{ae}$, $z_{ma}=z_{ma}(\rho_a,T_a)$ are quasi-neutrality condition and ion mean charge, $w_a(\rho_a,T_a)$ is the energy density of the anode plasma, T_a – temperature, v_a – velocity of atom, $P_a(\rho_a,T_a)$ pressure, j_a – current density. And at last, one must add an energy conservation law:

$$\rho_a\left(\frac{\partial w_a}{\partial t}+v_a\frac{\partial w_a}{\partial x}\right)=\frac{m\nu_{ea}j^2}{z_{ma}n_a e^2}- -P_a\frac{\partial v_a}{\partial x}+I_0(t)\exp(-\alpha x), \tag{5}$$

where α=4πnκ/λ [15] is the absorption coefficient for a specific wavelength λ_0 in vacuum and n is the refractive index. Constants κ, n are related to the following relationships:

$$n^2\left(1-\kappa^2\right)=\varepsilon, \quad n^2\kappa=\frac{\sigma}{\nu}, \qquad (6)$$

here ε, σ, v − media permittivity, the specific electrical conductivity, and frequency radiation, respectively.

Processes in a space of gas in front of an anode plasma can be described in frames of known drift-diffusive approximation models accounting ionization of ground states [18, 19]

$$\frac{\partial n_e}{\partial t}+V_f\frac{\partial n_e}{\partial x}-\frac{\partial}{\partial x}\left(n_e\mu_e E+D_e\frac{\partial n_e}{\partial x}\right)=n_e\nu_i, \qquad (7)$$

here $\mu_e=e/(mv_{en})$ is electron mobility, $D_e=(\mu_e kT_e)/e$ is diffusion coefficient, $V_f=v_a(x_f)$ – front velocity of anode plasma, $v_a(x_f)$ – hydrodynamic velocity of the anode plasma at its boundary.

$$\frac{\partial n_i}{\partial t}+V_f\frac{\partial n_i}{\partial x}+\frac{\partial\left(n_i\mu_i E\right)}{\partial x}=n_e\nu_i, \qquad (8)$$

here $\mu_i=e/(mv_{in})$ is ion mobility, $e_i=|e|$.

Taking into account that the gas in the discharge gap is dry nitrogen and its ions are molecular, one can ignore the influence of the electric field on their dynamics. In this case the equation (8) should be written in the following form:

$$\frac{\partial n_i}{\partial t}+V_f\frac{\partial n_i}{\partial x}=n_e\nu_i, \qquad (9)$$

$$\frac{\partial n_n}{\partial t}+V_f\frac{\partial n_n}{\partial x}=-n_e\nu_i\,. \qquad (10)$$

In expressions (7, 9, 11), as well as below, subscript e denotes electron, i denotes the ion, and n denotes the neutral atom. Also, v_i means the change rate of corresponding particle concentration due to ionization processes. The energy balance of electrons in the gas gap is determined by the following relation:

$$\frac{2}{3}\nu_{en}\varepsilon+m\frac{V_f^2 n_e}{2}-\frac{2m}{m_n}\nu_{en}kT_e-\\-\nu_i\left(kT_e+\frac{2}{3}I_i\right)=0\,, \qquad (11)$$

here $v_{en}=4n_0\sigma_0((kT_e)/(2\pi m))^{1/2}$ is elastic impact frequency and $v_i\approx v_{en}(2I_i/(kT_e))\exp(-I_i/(kT_e))$ is ionization one, $\varepsilon=e^2E^2/(2mv_{en}{}^2)$ is an electron energy gain in the electric field E

$$\frac{\partial E}{\partial x}=-\frac{e(n_e-n_i)}{\varepsilon_0}, \qquad (12)$$

where ε_0 is vacuum permittivity [20]. The collision frequencies are determined in Born approximation [19].

The following boundary conditions should be added to equations above: $\varphi_c=\varphi(t,\ 0)=0$. The bound "anode plasma – gas" is a contact discontinuity of media with different properties. This bound coincides with the anode surface at initial laser switch on. Let us denote its coordinates as $x_f(t)$. Then the following conditions must be satisfied at this boundary: $\varphi(x_f(t),\ t)=U(t_b)$; $P(t,\ x_f-0)=U(t_b)$; $P(t,\ x_f+0)$.

The following condition:

$$\left.\frac{\partial n_e}{\partial x}\right|_{x_{f-0}}=\left.\frac{\partial n_e}{\partial x}\right|_{x_{f+0}} \qquad (13)$$

serves to ensure the transparency for electrons at the boundary for electrons moving to the anode. And at last the following condition does not allow ions to pass through the boundary:

$$\left.\frac{\partial n_i}{\partial x}\right|_{x_{f+0}}=0\,. \qquad (14)$$

The condition on bound "anode plasma – gas" could be written in the following form:

$$e\left[n_i\left(t,x_f(t)\right)V_f\left(t,x_f(t)\right)-\right.$$

$$\left.-n_e\left(t,x_f(t)\right)V_e\left(t,x_f(t)\right)\right]+ \quad (15)$$

$$+\frac{1}{\varepsilon_0}\frac{\partial E\left(t,x_f(t)\right)}{\partial t}=\frac{U_b-RI(t)}{S}.$$

Here R – ballast resistance of measuring circuit, $I(t)$ – electrical current, S – surface cross-section equal to ≈0.05 – 0.1 of electron avalanche radius at the moment of its transition to plasma condition [16]. Also, the following initial conditions should be added. Before the laser pulse begins, both macroscopic velocities of the gas particles and the anode are equal to zero: T = 300 K, $E(t=0, x_f=d)=0$ – the electric field is defined by the solution of the Laplace equation.

Let us set a sharp boundary of the ionization wave front by the condition that the Coulomb value behind the ionization wave front is equal to zero. This is equivalent to neglecting electron diffusion in equation (7). Then, condition (15) remains valid for this boundary. The boundary between the streamer molecular plasma and the anode plasma turns into a contact discontinuity. However, due to the plasma quasi-neutrality, the current density is continuous on both sides of this discontinuity. In this study, the breakdown is characterized by complete filling in the discharge gap by quasi-neutral plasma. At a moment close to t_s the relation (15) may be rewritten in the following form:

$$-en_e\left(t,x_i(t)\right)\mu_e E(t,x_i(t))+$$

$$+\frac{1}{\varepsilon_0}\frac{\partial E\left(t,x_i(t)\right)}{\partial t}=\frac{U_b-RI(t)}{S}. \quad (16)$$

Note that, if one neglect the volume discharge relaxation after breakdown, then $t_b \to t_s$. Due to analysis of the experimental results presented on Fig. 4, 5, the electrical breakdown at the final stage can be considered as a non-equilibrium phase transition between two phases. The first phase is cold nitrogen in which the current is limited by the space discharge. The second one is a low-temperature quasi-neutral plasma with no such limitations. Both second-order equilibrium phase transitions [21] and non-equilibrium phase transitions [22] are characterized by a power-law behavior of their parameters near singular (critical) points. Then, the ionization wave coordinate x_i as it approaches the cathode can be described as follows:

$$x_i \approx a\left(t_*-t\right)^{\beta} \quad (0<\beta<1), \quad (17)$$

where a, β parameters can be defined by numerical modeling or experimentally.

Then, the velocity of the ionization wave will be as follows:

$$C_i=\frac{dx_i}{dt}\approx -a\beta\left(t_*-t\right)^{\beta-1}. \quad (18)$$

If we suppose that the scalar electric potential for a moment near t_* is the following: $\varphi(x)=U_b\cdot(x/x_i)$, then

$$E=-\frac{\partial\varphi}{dx}=-\frac{U_b}{x_i}\approx -\frac{U_b}{a\left(t_s-t\right)^{\beta}}. \quad (19)$$

Taking into account the relations (17)–(19), the equation (16) can be written as follows:

$$en_e(x_i)\mu_e\frac{U_b}{a\left(t_*-t\right)^{\beta}}- \quad (20)$$

$$-\frac{\beta U_b}{\varepsilon_0 a\left(t_*-t\right)^{\beta+1}}=\frac{U_b-RI}{S}$$

The first term on the left side of condition (20) is determined by the electron transfer, and the second one is determined by the surface charge change (electric field) on the ionization wave front. After the discharge gap is completely filled with quasi-neutral plasma, the charge transfer in this discharge gap can be described in terms of the magnetohydrodynamics [19]. As it follows from the balance equation (10), the electron concentration implicitly depends on the electric field by the dependence of the ionization frequency on temperature (energy). This reason provides the finite values of the voltage drop in equation (20) observed in the experiment.

As regards the index β in Landau theory [22], it was found to be 1/2 for equilibrium second-order phase transitions. It has been shown [23] that the index β=1/2 gives the constancy of the power released at the front of the slit growing into the conductor. The model of the stratification of a conductor exploded by an electric current was built in the paper above. Since the streamer (conducting phase) grows into the non-conducting phase (molecular gas) in the gas gap, one can expect β=1/2 for this case.

Conclusion

The preliminary and simple estimation of the boundary velocity of the anode plasma initiated by laser radiation does not correspond to the experimental data observed. The suggested simple model explicitly considers the dependence of the triggering on the electric field strength and generation in the front boundary of the anode quasi-neutral plasma of the gaseous density of the cathode-directed streamer. In further work we suppose to develop the model toward considering the multidimensionality and non-linearity of physical processes occurring in the evolution of laser-initiated plasma in an electric field.

Acknowledgments / Благодарности

The research was carried out with financial support of Russian Science Foundation and Government of Sverdlovsk Region, project No. 22-29-20058.

Исследование выполнено при финансовой поддержке Российского Научного Фонда и Правительства Свердловской области, проект № 22-29-20058.

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