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Plasma instability in a laser controlled high-voltage switch for RADAN type electron accelerator

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Abstract. The paper presents the results experimental investigation of triggering a high-voltage gas gap by YAG: Nd^{3+} laser. The gas gap was used as the primary switch of a high-current pulsed *e*-beam RADAN-type accelerator. The operating regime with the instability and delay time appeared to be minimal was experimentally found. The developed laser controlled switch and the found operating regimes sustain the instability not more than 0.3 ns. The physical mechanisms determining the switch-on delay and the obtained level of instability are discussed. The processes on the ionization wave front seem to be determined mainly both by the absorption/excitation of gas atoms and the effects of a high-field domain proposed.

Keywords: laser controlled switch, triggering stability.

1. Introduction

The laser-induced gas breakdown [1] is widely used in high-pressure gas gaps with optical control [2, 3]. The stability of the switch transition time to the conducting state is important both for commutation losses decrease and when it is necessary simultaneously to fire up several devices operating on a conjoint load. The most significant advantage of optically controlled switches in comparison with electrically triggered analogs is the isolation of control circuits from commutated ones. Despite decades of development, this issue determines the interest in the improvement of such switches even in the present time. That is why the activity aimed at their development is underway now, in particular, new switches have been patented quite recently [4]. The data we obtained earlier [5] could not be explained in frameworks of simple theoretical models [6]. Using this approach it is hardly possible to explain the dependence of the breakdown delay time and its instability (jitter) on applied voltage to the gas gap. Since an initial laser plasma formation is not related to a voltage, i.e. a field strength in a gap, because initial laser plasma characteristics are determined by the laser pulse only. Moreover one can easily estimate the mean velocity of an ionization wave traveling across the gas gap for such case. It has an order of magnitude about 10^6 m/s. The obtained estimation cannot be described by well-known laser-supported detonation wave (LSD) model [7]. The point is the velocity of LSD does not exceed 10^4 m/s in similar conditions [8, 9]. Thus, the purpose of this article is an experimental study and a theoretical description of the processes occurring during the formation and development of laser plasma in an electric field to work out ultimately practical recommendations for the creation of high-voltage gas switches with subnanosecond operation stability.

2. Apparatus and experimental results

Both the experimental setup and measurement technique we used are described in detail in our recent papers [5, 10] and here brief description is presented only. The gas gap we used was a primary switch of the RADAN-300 *e*-beam accelerator [11]. This switch was modified a little bit for the laser triggering. The Q-switched YAG:Nd^{3+} LS-2134 laser pulses (JV LOTIS TII, Belarus, https://www.lotis-tii.com) having energy 200 ± 0.5 mJ, FWHM = 14 ns, and wavelength $\lambda = 1064$ nm to fire the switch were used. It is important to note the laser radiation was focused on the gas gap anode. The focused laser radiation spot has a diameter about $D = 2 \cdot R_f = 2 \times 10^{-4}$ m and the lens focal point was adjusted behind the anode surface to avoid uncontrolled optical breakdown of the gas in the interelectrode gap of $d = 3$ mm distance.

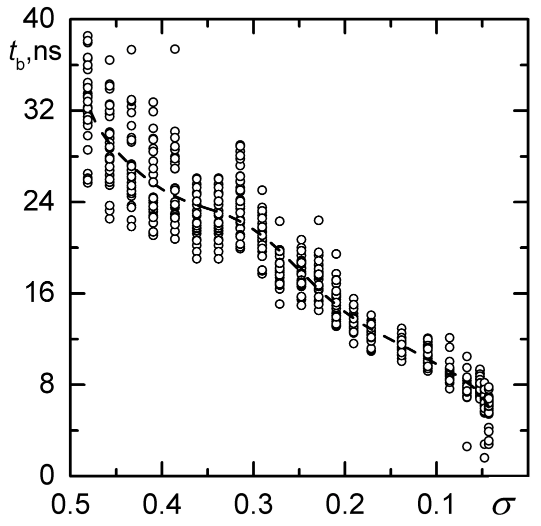

Fig.1. The dependency of switch-on delay time t_b vs relative switch-on voltage σ.

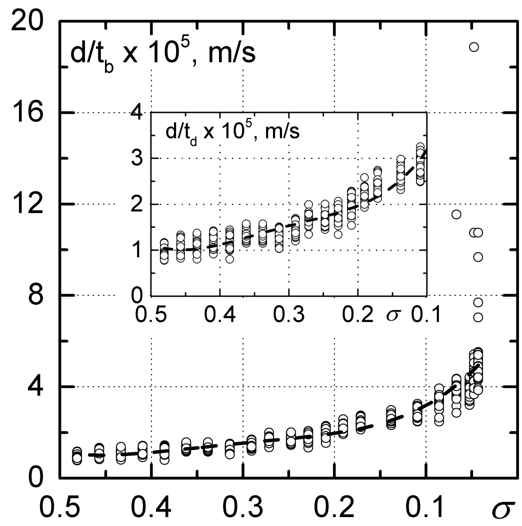

Fig.2. The dependency of mean velocity of ionization wave vs relative switch-on voltage σ.

The choice of anode for laser plasma ignition was stipulated by the intent to diminish switch trigger delay [12] which can lead to lower triggering jitter we expected. For anode voltage $U_a = 190$ kV and grounded cathode of the switch, the calculated undistorted by primary laser plasma electric field maximum had a value of $E_{max} = 7.1 \cdot 10^7$ V/m. The switch was filled in by dry nitrogen at pressure $P = 4$ MPa. The laser radiation pulse could be applied with a controlled time delay relative to the onset of the charging of the accelerator double forming line. As a result, it was possible to change the relative gap voltage $\sigma = (U_s - U_b)/U_s$ in a broad range. Here U_b – laser controlled switch-on voltage, U_s – gap self-breakdown voltage. The breakdown delay time t_b relative to the laser pulse beginning was observed experimentally. Fig.1 presents this breakdown time t_b measured in dependence on the voltage σ applied to the gap. Fig.2 presents an estimation of the mean velocity of ionization wave traveling across the gas gap also in dependence on the voltage. To characterize the switch triggering instability (jitter) the confidence limits Δt of the random error of t_b value for confidence level $p = 0.95$ calculated according to [13] was used. These estimations are presented in Fig.3.

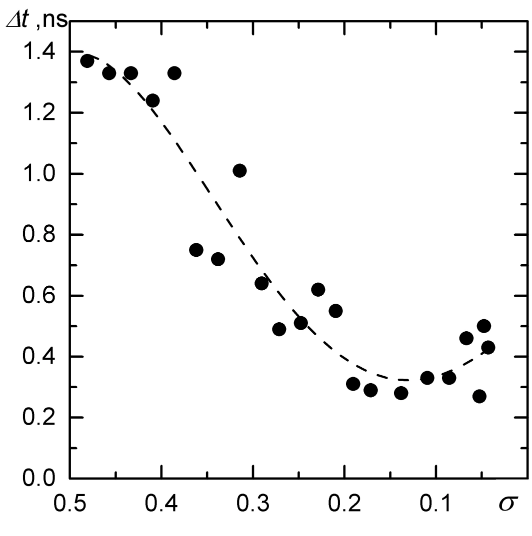

Fig.3. The dependency triggering instability Δt vs relative switch-on voltage σ.

3. Discussion

3.1. Preliminary estimates

To find the size of the metal volume heated by laser radiation, several methods can be used. First, assume the laser pulse energy is distributed on the anode surface according to the normal law [14]:

$$\Phi_u(x) = \frac{1}{\delta\sqrt{2\pi}} \exp\left(-\frac{1}{2}\left(\frac{x-\xi}{\delta}\right)^2\right), \tag{1}$$

where $\xi = 0$, $\delta = 0.000025$ m in order to provide focus spot diameter $D = 2 \cdot R_f = 2 \cdot 10^{-4}$ m required for our case. The mean squared radius of distribution (1) is equal to $R_s = [(x^2)_u]^{0.5} = 2.49 \cdot 10^{-5}$m, i.e. the bulk where laser pulse energy was deposited entirely. The volume of this bulk is $V_s = 4\pi R_s^3/3 = 6.53 \cdot 10^{-14}$ m^3. This volume contains $N_a = 5.54 \cdot 10^{15}$ atoms, each of them has energy of $W_{pa} = 213.86$ eV/atom, which is 49.85 times greater than the iron binding energy ($\Lambda_s = 4.29$ eV/atom). We assume the anode consists of pure iron instead of stainless steel we really use to simplify the modeling process. The maximum value of the speed of scattering atoms $C_a \approx (W_{pa}/(\gamma-1))^{0.5} = 2.35 \cdot 10^4$ m/s, where D_a is the unified atomic mass unit and $\gamma = 5/3$ is the adiabatic index in the assumption of atom interaction neglect for this estimations. These estimation poorly corresponds to the discharge development time $t_b = d/C_a = 127.4$ ns (compare with experimentally obtained times, Fig.1).

Even we use another method for the estimation for the case when the irradiated volume is assumed as the cylinder with a base equal to the focal spot and a height $h = 0.5 \cdot \lambda = 532$ nm [15], where λ is laser radiation wavelength. So one can estimate the volume $V_s = \pi R_f^2 \cdot h = 1.67 \cdot 10^{-14}$ m^3 which contains about $N_a = 1.43 \cdot 10^{15}$ atoms. Accounting the laser radiation energy one can estimate also the atom velocity $C_a = 4.65 \cdot 10^4$ m/s. The last one determines the overlap time of gap distance d by the plasma $t_b = 64.45$ ns. Such estimation gives the upper bound value. Moreover one can obtain the lower bound estimation assuming irradiated volume as a sphere with the focus spot radius. So this volume $V_f = 4\pi R_f^3/3 = 4.19 \cdot 10^{-12}$ m^3 containing $N_a = 3.55 \cdot 10^{17}$ atoms. In this case, each atom can get from the laser pulse only $W_{pf} = 3.34$ eV/atom, i.e. $W_{pf}/\Lambda_\varepsilon = 0.78$. Generally saying, it is not enough for ionization and the anode material expansion will occur mainly in the form of neutral atoms. The latter can not lead to the electric field distortion i.e. forming a high-field domain (HFD) and as result any significant delay decrease of discharge in comparison to the self breakdown of discharge gap in the absence of laser triggering. It should be noted that the upper bound estimates are also in poor agreement with our experiment, in which it was found that the discharge development time i.e. breakdown of the interelectrode gap and jitter depends nonlinearly on the electric field. The value of $\sigma = 0.1$ corresponding to the jitter minimum gives a lower bound estimation of discharge development velocity $C_a = (2.5–3.75) \cdot 10^5$ m/s for $t_b = (2.5–3.75)$ ns (see Fig.2).

3.2. Simple model

Estimates above show the necessity to take into account the following for modeling: (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 the energy to heavy atom/ion component; (3) the external electric field potential is maximal at the anode side $\varphi_a = U(t)$ (cathode is grounded in our case, $\varphi_c = 0$) and therefore it decelerates electrons and accelerates 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.

In constructing our model of the laser plasma dynamics the approach proposed in [16] is used. Taking into account laser pulse FWHM ~10^{-8} s and the settling times of LTE ~10^{-13} s one can limit the process model for first approximation on the single-fluid, one-temperature approach. Then the model equations will be the following:

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

mass conservation law.

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

motion equation.

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

generalized Ohm's law.

Here $\rho_a=(M\cdot A+\bar{z}_a m)n_a$ is a density, n_a – concentration, M – unified atomic mass unit, A = 56 for iron. $\bar{z}_a n_a = n_{ae}$, $\bar{z}_a=\bar{z}_a(\rho_a, T_a)$ are quasi-neutrality conditions and ion mean charge, $w_a(\rho_a, T_a)$ is the energy density of the anode plasma, T_a – temperature, v_a – atoms' velocity, $P_a(\rho_a, T_a)$ pressure, j_a – current density. And at last, one has to add energy conservation law:

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

Where $\alpha = \pi n\kappa/\lambda$ [15] is the absorption coefficient for specific wavelength λ_0 in vacuum and n is the refractive index. Constants κ, n are related by the following relationships:

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

here ε, σ, ν – permittivity, specific electrical conductivity, and frequency radiation, respectively.

Processes in a space of gas in front of anode plasma can be described in frames of known drift-diffusive approximation models accounting the ionization both of ground and excited states as well as by photoionization [17, 18].

$$\frac{\partial n_e}{\partial t}+V_f\frac{\partial n_e}{\partial x}-\frac{\partial}{\partial x}\left(n_e\mu_e E+D_e\frac{\partial n_e}{\partial x}\right)=\dot{n}_e+I_{ph}, \tag{7}$$

here $\mu_e = e/m\nu_{en}$ electron mobility, $D_e = \mu_e kT_e/e$ – diffusion coefficient, V_f – front velocity of anode plasma, I_{ph} – photoionization.

$$\frac{\partial n_i}{\partial t}+V_f\frac{\partial n_i}{\partial x}+\frac{\partial(n_i\mu_i E)}{\partial x}=\dot{n}_e+I_{ph}, \tag{8}$$

here $\mu_i = e/m\nu_{in}$ ion mobility.

$$\frac{\partial n_n}{\partial t}+V_f\frac{\partial n_n}{\partial x}=-\dot{n}_e-I_{ph}-\dot{n}_n^*, \tag{9}$$

$$\frac{\partial n_n^*}{\partial t} + V_f \frac{\partial n_n^*}{\partial x} = -\dot{n}_n^* . \tag{10}$$

In expressions above (7–10) as well as below subscript *e* denotes electron, *i* denotes ion, and *n* denotes neutral atom. Superscript “*” means the excited state of an atom.

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

here $\nu_{en} = 4n_0\sigma_0(kT_e)^{0.5}/(2\pi m)^{0.5}$ is elastic impact frequency and $\nu_i \approx \nu_{en}(2I_i/kT_e)\exp(-I_i/kT)$ is ionization one, $\varepsilon = e^2E^2/(2m\nu_{en})$ is an electron energy gain in the electric field E.

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

Equation (11) does not take into account losses of the atoms' excitation and collision frequencies are determined in Born approximation [18].

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

$$\varphi(x_f(t),\ t) = U(t_b);\ P(t,\ x_f - 0) = U(t_b);\ P(t,\ x_f+0) \tag{13}$$

The condition:

$$\left.\frac{\partial n_e}{\partial x}\right|_{x_{f-0}} = \left.\frac{\partial n_e}{\partial x}\right|_{x_{f+0}} \tag{14}$$

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

$$\left.\frac{\partial n_i}{\partial x}\right|_{x_{f+0}} = 0 \tag{15}$$

Condition on bound “anode plasma – gas” could be denoted in the following form

$$e\left[n_i\left(t, x_f(t)\right)V_i\left(t, x_f(t)\right) - n_e\left(t, x_f(t)\right)V_e\left(t, x_f(t)\right)\right] + \frac{1}{\varepsilon_0}\frac{\partial E\left(t, x_f(t)\right)}{\partial t} = \frac{U_b - RI(t)}{S} \tag{16}$$

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 condition should be added. Before the laser pulse begins both macroscopic velocities of gas and anode particles 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.

4. Conclusion

The experimental results the main of which was finding of jitter minimum in the range relative gap voltage $\sigma = (U_s - U_b)/U_s = 0.15$–$0.1$ were obtained. The performed estimates for the velocity of the boundary of the anode plasma initiated by laser radiation do not correspond to the observed experimental data. The suggested simple model explicitly takes into account the dependence of the triggering time 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. We propose in further work the model proposed will undoubtedly be developed in the direction of taking into account the multidimensionality and nonlinearity of physical processes occurring during the evolution of a laser initiated plasma in an electric field.

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5. References

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