The study of instabilities role of plasma in the high-voltage discharge formation initiated by optical radiation at high pressures in high-voltage optically triggered switches

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Abstract. The paper presents the experimental results of triggering a high-voltage gas gap by YAG: Nd³⁺ laser radiation. The gas gap was used as the primary switch of a high-current pulsed e-beam RADAN-type accelerator. As a result, an operating regime when the instability and delay time appeared to be minimal was experimentally found. The developed gas gap and the found operating regimes sustain the switching instability no more than 0.3 ns. The physical mechanisms determining the switch-on delay and the obtained level of instability are discussed.

1. Introduction
The laser-induced gas breakdown [1] is widely used in high-pressure gas gaps with optical control [2, 3]. A switch transition time to the conducting state significantly determines the commutation losses. The stability of the operation is also important especially when it is necessary to fire several devices simultaneously on a conjoint load. One of the most significant advantage of optical controlled switches in comparison with electrically triggered analogs is the galvanic isolation of control circuits from commutated ones. Also, the electrical method of firing is difficult to use in pass-through dischargers when there is no grounded electrode at all [4]. Despite decades of development, this determines the interest in the improvement of optically triggered switches even in the present time and the activity aimed at their development is underway now, in particular, new switches controlled by optical radiation has been patented quite recently [5, 6].

2. Apparatus and experimental results
The main part of the experimental setup we used in the paper was the gas gap of the RADAN 300 e-beam accelerator modified for the laser triggering which was described in detail in the paper [7]. So it is worth noting only its main features. To fire this high-voltage switch the pulses of YAG:Nd³⁺ laser with energy of 200 mJ, FWHM = 14 ns, and wavelength $\lambda = 1064$ nm were used. It is important to note the laser radiation was focused on the gas gap anode. The spot diameter was about 0.2 mm and the focal point of the lens was adjusted behind the anode surface to avoid uncontrolled optical breakdown of the gas in the interelectrode gap having the distance of $d = 3$ mm. Focusing on anode was chosen to provide faster triggering with lower jitter [8]. Electric field simulation example for anode voltage $U_a = 190$ kV, cathode is grounded is shown in figure 1. One can see the 2 mm diameter hole in the cathode to pass through laser radiation practically only slightly distorts the electric field $E$
in the gap. In this case, the calculated electric field maximum had a value of $E_{\text{max}} = 7.1 \times 10^5$ V/cm. The switch was filled in by dry nitrogen and pressurized up to $p = 4$ MPa. The laser radiation pulse could be applied to the anode with the required delay with respect to the onset of the charging of the double forming line (DFL) of the RADAN 300 accelerator. So one could vary the ratio of a difference between the gas gap self-breakdown voltage and switch-on voltage to the self-breakdown voltage

$$\sigma = (U_s - U_{\text{switch}})/U_s,$$

where $U_{\text{switch}}$ – switch-on (we say, laser controlled breakdown) voltage, $U_s = 210$ kV – self-breakdown voltage for mentioned above pressure and interelectrode gap.

![Figure 1](image1.png)

**Figure 1.** Gas gap configuration and typical electric field pattern. Anode voltage $U_a = 190$ kV, the cathode is grounded. A – anode, C – cathode.

![Figure 2](image2.png)

**Figure 2.** Oscillogram of the switch operation in the laser control mode. 1 – voltage of the DFL charge, 2 – laser pulse, $t_b$ – delay time of switch-on relatively onset of the laser pulse.

The delay time $t_b$ at which the switch was fired (the fast voltage drop-down at oscillogram of DFL charging, figure 2, 1) was recorded relative to the laser trigger pulse. The DFL voltage drop-down simultaneously triggered the oscilloscope. The time at which the switch was fired was recorded relative to the laser trigger pulse, which simultaneously triggered the oscilloscope (figure 2). Since DFL charge voltage slowly rises up in the microsecond time domain one could obtain $t_b$ for different $\sigma$ by simply shifting laser pulse with respect to the DFL charging onset. The examples of such measurements for different $\sigma$ are shown in figure 3.

The summarized data obtained are shown in figure 4. One can see the decrease of the time delay of gas gap firing $t_b$ with decrease $\sigma$. Nevertheless, the stability of the switch-on seems to depend on $\sigma$ non-monotonously. At $\sigma < 0.1$ when the switch begins to operate close to the voltage of self-breakdown the jitter appears to begin increasing. The gas gap switch-on jitter $\Delta t$ has been defined as a root-mean-square deviation confidence interval of the measured $t_b$ values. The results of the jitter calculations for the confidence level $\alpha = 0.95$ for 30 pulses for each $\sigma$ are shown in figure 5.
3. Discussion

We excluded from consideration the simple gas gap overlapping by laser-supported detonation wave (LSD) [9]. The point is the velocity of LSD does not exceed $10^4$ m/s in similar conditions [10, 11]. So the typical process time would be in the sub-microsecond time domain for gas gap distance is about
1 mm, i.e., quite far from the nanosecond time domain switching-on we are aiming at. And even the LSD velocity would be $10^4$ m/s, then during a laser pulse of $\sim 10$ ns, it would travel only $10^{-1}$ mm, i.e., less than 10% of the distance between the electrodes. And even the LSD velocity would be $10^5$ m/s, as was observed at significantly higher laser radiation power densities [12], this velocity is not sufficient for the short resulting delay for the terms of pressure and size of the discharge gap we used. At the same time, the switch-on of a high-pressure gas gap in conditions close to self-breakdown can be estimated using the Rompe-Weitzel model [13]:

$$p \cdot t_s \approx K_s \cdot \left(p / E\right)^2 \cdot \alpha^{-1},$$

(1)

here $p$ is pressure in atm, $E$ is the electric field in V/cm, $K_s$ is the coefficient depending on the voltage pulse front duration ($K_s \approx 10-20$), and $\alpha = 0.8-1$ atm-cm$^2$·s$^{-2}$·V$^{-2}$ is a gas constant for nitrogen. In the field switch-on time is $t_s = 1.9-0.8$ ns according to this model.

Figure 6. Gas gap field pattern without laser plasma plume (a) and axial field distribution (b). $E_{\text{max}} = 7.1 \cdot 10^5$ V/cm in cathode region.

Figure 7. Gas gap field pattern for laser plasma plume approximated by hemisphere with radius 0.2 mm (a) and axial field distribution (b). $E_{\text{max}} = 13.2 \cdot 10^5$ V/cm.
One can compare this estimated switch-on time value for non-distorted electric field (figure 6) with experimentally obtained value $t_b \approx 10$ ns for $\sigma = 0.1$ (see figure 4).

Figure 8. Gas gap field pattern for laser plasma plum approximated by hemisphere with radius 0.4 mm (a) and axial field distribution (b). $E_{\text{max}} = 15.1 \times 10^5$ V/cm.

Figure 9. Gas gap field pattern for laser plasma plum approximated by hemisphere with radius 0.6 mm (a) and axial field distribution (b). $E_{\text{max}} = 16.7 \times 10^5$ V/cm.

The domain of the intensive field in front of the plasma plum appears to be forming. Figures 7-11 show the field increases in this domain during the propagation of plasma plume along the gas gap axis towards the cathode for $\sigma = 0.1$ and for plasma plume. The last one was approximated by hemisphere in these simulations. For this case, the difference in switch-on time according to the Rompe-Weitzel model and the experimental obtained one is more obvious.

According to Rompe-Weitzel model for $E = 15.1 \times 10^5$ V/cm (figure 8) switch-on time will be $t_s = 0.44 - 0.17$ ns i.e. at least is one and half orders of magnitude less than the time $t_d$. Thus, the contribution of this value $t_s$ both to switch-on delay and jitter seems to be negligible and the main reason for the delay and jitter forming lays in the phase of initial plasma plum forming and it is at the stage of discharge formation that their main distinctions are formed [14]. Another words, the initial
phase is decisive and as soon as the initial plasma plum is formed then the gas gap overlapped very quickly for the time less 1 ns. However, in this case, one should not forget the experimentally observed jitter minimum (see figure 5), in our opinion, is determined by nonlinear electrophysical processes on the ionization wavefront (the axial electric field dependence on the size plasma plume of shown in figures 6-11 (b)). In our opinion, the most important of the physical mechanism that determines the minimum jitter is the instability of the ionization wave front, which is facilitated by the formation of a strong electric field domain and, as a consequence, the width decrease of the ionization wave front.

Figure 10. Gas gap field pattern for laser plasma plum approximated by hemisphere with radius 0.8 mm (a) and axial field distribution (b). $E_{\text{max}} = 17.0 \times 10^5 \text{ V/cm}$.

Figure 11. Gas gap field pattern for laser plasma plum approximated by hemisphere with radius 1.0 mm (a) and axial field distribution (b). $E_{\text{max}} = 17.64 \times 10^5 \text{ V/cm}$.

4. Conclusion
Thus the data obtained earlier in [7] could not be explained in frameworks on simple theoretical models [13]. Our analysis of the distribution of the axial electric field of the gas gap for different sizes of a laser plasma plume formed on the anode shows its dynamics is similar to that one of the
ionization wave front in a cathode propagating streamer as a result of the transfer of resonance radiation along with associative ionization [15]. In our case, the processes in the front of the ionization wave seem to be determined mainly both by the absorption and excitation of gas atoms by laser radiation and the effects of a strong electric field we propose.

The further activity we propose will be tagged on the experimental and theoretical study of the dynamics of the plasma plume initially formed on the anode surface.

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