Laser-triggered gas switch with subnanosecond jitter and breakdown delay tunable over ∼0.1-10 ns governed by the spark gap ignition angle

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We created a practical air-filled switch triggered by a $\sim 10^9$ W picosecond laser beam with a slightly variable breakdown delay and low jitter. The switch relies on the spark gap with a coaxial geometry, which is ignited by a focused laser beam directed at a certain angle to the gap axis. The switch is integrated with a high-voltage cable generator operating at a constant negative voltage of up to 50 kV. We demonstrate that, by just varying the ignition angle of the spark gap, one can achieve variable breakdown delay tunable within $\sim$ 0.1–10 ns with $\lesssim 1$ ns jitter. Empirical dependences of switching characteristics of the developed device on the ignition angle are obtained. We demonstrate that, combined with variation of the ignition beam energy and charging voltage, variation of the spark gap ignition angle provides superior control over the gap switching characteristics without complicating the switch design. The proposed approach to driving the switching characteristics appears highly promising for designing compact Laser-Triggered Gas Switches with variable temporal characteristics and achieving precise synchronization between high-voltage and measuring equipment.

Keywords: laser triggering; spark switch; atmospheric discharge; high current electronics

Introduction – Laser triggering driven by a laser-induced breakdown[1–4] of a gaseous medium is of considerable interest for fundamental and applied science[5–9] owing to numerous unique properties of the generated highly ionized and conductive plasma filament[10–13]. In particular, such filament can be initiated with extremely low temporal and spatial jitters[12,13], which makes it promising for guiding flows of electromagnetic energy of high power and density in coaxial or strip waveguide lines[14–21]. Basically, the laser-induced breakdown is employed in the so-called Laser-Triggered Gas Switch (LTGS) that relies on a standard gas-filled spark gap ignited by a focused laser beam directed along or at a certain angle (ignition angle) to the gap axis. Depending on the ignition angle, the LTGS delay time and jitter vary from hundreds of picoseconds to hundreds of nanoseconds and longer[21]. There are also prerequisites to the fact that, without changing the characteristic parameters (pressure, gas composition, gap length, etc.) of the discharge medium, one can readily tune the breakdown delay of the LTGS with low jitter by just varying the ignition angle. This effect turns out to be extremely attractive for achieving precise synchronization between high-voltage and measuring equipment, especially when the employed diagnosing device (ultrafast ICCD, laser, etc.) has its own delay time and jitter. However, the effect of the ignition angle of the spark gap on its switching characteristics is not studied in sufficient detail, and, hence, a number of technical advantages associated with this effect have been missed.

In spite of the fact that, in respect to LTGSs, there is still no comprehensive theory describing the relationship between their temporal characteristics and the plasma formation processes in the spark gap, in this Letter, we try to understand qualitatively how exactly the ignition angle of the gap governs its switching characteristics. In this systematic study, we acquire the empirical dependencies of the temporal characteristics of the created LTGS on the ignition angle. It is assumed that the effect of the ignition angle on the LTGS characteristics is stipulated by the different intensities of the ionization processes in the regions with and without laser pre-ionization, as well as by the scales of these regions. The reported findings provide a means to greatly simplify the designs of the LTGSs with variable temporal characteristics by just varying the spark gap ignition angle.

Experimental setup – The scheme of the setup is presented in Fig. 1(a). To clarify the effect of the ignition angle (α) on the LTGS characteristics, i.e., on the temporal characteristics of the generated high-voltage pulse, we created a simple LTGS based on a two-electrode spark gap with a coaxial configuration (Fig. 1(b)). The gap with a length of $\approx$ 3 mm was filled with air up to 7 bar. The electrodes were made of stainless steel and had rounded tips. To develop the high-voltage generator providing the pulse with the highest amplitude in the traveling wave mode, we needed to achieve the maximum possible value of air pressure from the compressor, which was limited by the particular instrument. The LTGS was connected to a high-voltage DC power supply (up

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to 50 kV, negative polarity) through a high-voltage cable with a length of 3 m and impedance of 75 Ω and a ~ 1 GΩ resistor. The LTGS output was coupled to a coaxial capacitive voltage divider through a matched transmission line. The divider has a temporal resolution better than 1 ns; its design is described in[22] in detail.

A Q-switched Nd:YAG laser with active mode locking (Lotis LS-2151) providing 1064 and 532 nm emission with the pulse energy up to 80 mJ was used to trigger the LTGS. The pulse duration at 1064 nm was 100 ps. The laser beam energy was controlled with a 10% accuracy. The output laser beam (both harmonics) with a diameter of 9 mm was focused by a lens with a diameter of $D =$ 10 mm and a focal length of $F = 50$ mm. The power density of the laser radiation at 1064 nm (bearing $\approx 70\%$ of the ignition beam energy) was 10^{10}–10^{11} W/cm^2 in the focal spot region. Real-time precise adjustment of the spark ignition region was done by imaging integral glows of the initiated "laser sparks". A short-focus lens (Canon EF-S 18–55 mm) combined with a digital camera (Canon EOS 1100D) was employed to detect the glow along the ignition beam direction. The adjustment accuracy of a focusing lens is essential for obtaining relevant temporal characteristics of an LTGS, see, e.g., in[3]. Indeed, when a short-focus lens is used, a part of the focused radiation is rereflected from the glass window of the LTGS and significantly degrades the lens. Nevertheless, by igniting the spark gap at oblique angles, as shown in the inset of Fig. 1(b), reliable LTGS operation can be achieved since the rereflected radiation gets away from the lens. The instant of the ignition beam arrival at the gap was determined by a photodetector (Thorlabs DET10A/M) with a rise time of 1 ns, which was coupled with a green glass filter having 40% transmittance within 450-600 nm. The photodetector was placed near the LTGS at such an angle that it was irradiated only by the part of the radiation rereflected from the glass window of the LTGS, i.e. it was covered by the LTGS body, and, hence, did not register the glow from the spark gap. The signals from the photo and voltage detectors were recorded by a 1.5 GHz digital oscilloscope (HP Infinium 54845A). The registration accuracy of the ignition beam arrival was ≈ 0.3 ns with all optical and signal cable delays, as well as the sampling frequency (8 GSa/s) of the oscilloscopes taken into account.

Experimental results – The breakdown delay of the developed LTGS was defined as the time difference between the ignition beam arrival at the spark gap and the onset of the high-voltage pulse, see Fig. 1(c). The jitter (LTGS reproducibility) was taken as the average deviation of the breakdown delay from the mean value. We found out that, to achieve precise LTGS operation with the lowest jitter at each ignition angle, it is sufficient to direct the ignition beam towards the cathode at an acute angle to the gap axis. Indeed, the beam should arrive approximately at the top (region A in Fig. 2) of the rounded cathode, where the electric field is expected to be the highest. In contrast to this, the beam focusing towards the anode entails stochastic jitter and delays as in the case of the beam arrival at the region far ($\gtrsim 100$ μm) from the top of the corresponding electrode, which is highly unfavorable for precise LTGS guiding. Additionally, the focusing lens has to be initially (before high voltage is applied) adjusted so as to provide the initiation of a "laser spark" at a minimum laser pulse energy of ≈ 3 mJ, with the spark spaced ~ 1 mm from the cathode. The spark we registered was ≈ 300 μm in length. With increasing the laser beam energy up to 80 mJ, expansion of the laser spark towards the cathode and back along the path of the ignition beam was observed. In this case, the spark reached the length comparable to the gap length, and its structure became complex and inhomogeneous, see Fig. 2(a). The latter fact can be due to lens aberrations and nonlinear refraction of the ignition beam in the focal spot region[23]. After applying a high voltage, when the gap was ignited at a certain angle to its axis, the resultant spark channel developed along a zigzag path, see Figs. 2(b), (c), (d). Its images were obtained at $U_0 \approx 45$ kV and different ignition beam energies. By analyzing the images in Fig. 2, one can assume that, at high ignition beam energies (up to 80 mJ), the spark channel arises near the region (denoted as A in Fig. 2) on the cathode surface, whereinto the ignition beam arrives. The channel then travels along the path of the ignition beam (towards it) to some "point" (denoted as D) from which the channel makes a sharp turn in the anode direction. At low ignition beam energy, the resultant spark channel can originate from the regions on the cathode surface far from the region of the ignition beam arrival, see Fig. 2(c). Meanwhile, the length of the channel path becomes comparable to the gap length, see Fig. 2(d).

Following an empirical approach to studying the LTGS switching characteristics, it may be assumed that the effect of the ignition angle on the LTGS characteristics is associated with the different intensities of ionization processes in the regions with and without laser pre-ionization as well as with the scale of these regions. In particular, the scale of the region without pre-ionization may be characterized by the distance Δ (see Fig. 2) from the anode to the region with the laser spark. The scale of this region has the highest impact at $\Delta \gtrsim 1$ mm (Fig. 2) with $U_0 \approx 45$ kV and $Q \approx 75$ mJ. Figures 3 and 4, demonstrate the dependences of the LTGS delay and jitter on charging voltage U_0 and ignition beam energy Q for ignition angles $\alpha \approx 40°$, $50°$, and $60°$ or, correspondingly, for $\Delta \approx 0.5$, ≈ 1.4, and ≈ 1.9 mm. Each experimental point for the delay and jitter dependences was obtained by averaging over ~ 10–20 shots. Here the characteristic range of ignition angles providing short LTGS delay with low ($\lesssim 1$ ns) jitter is $\alpha \sim 40°$–$60°$. For $\alpha > 60°$, the delay and jitter sharply rise by more than several tens of nanoseconds. The lower boundary $\alpha \approx 40°$ of the angle range is due to the employed electrode geometry and LTGS design. It is seen in Fig. 4 that, at $\alpha \approx 40°$ ($\Delta \approx 0.5$ mm), $U_0 \approx 45$ kV, and $Q \gtrsim 15$ mJ, the delay and jitter dramatically drop to the values comparable with the mea-

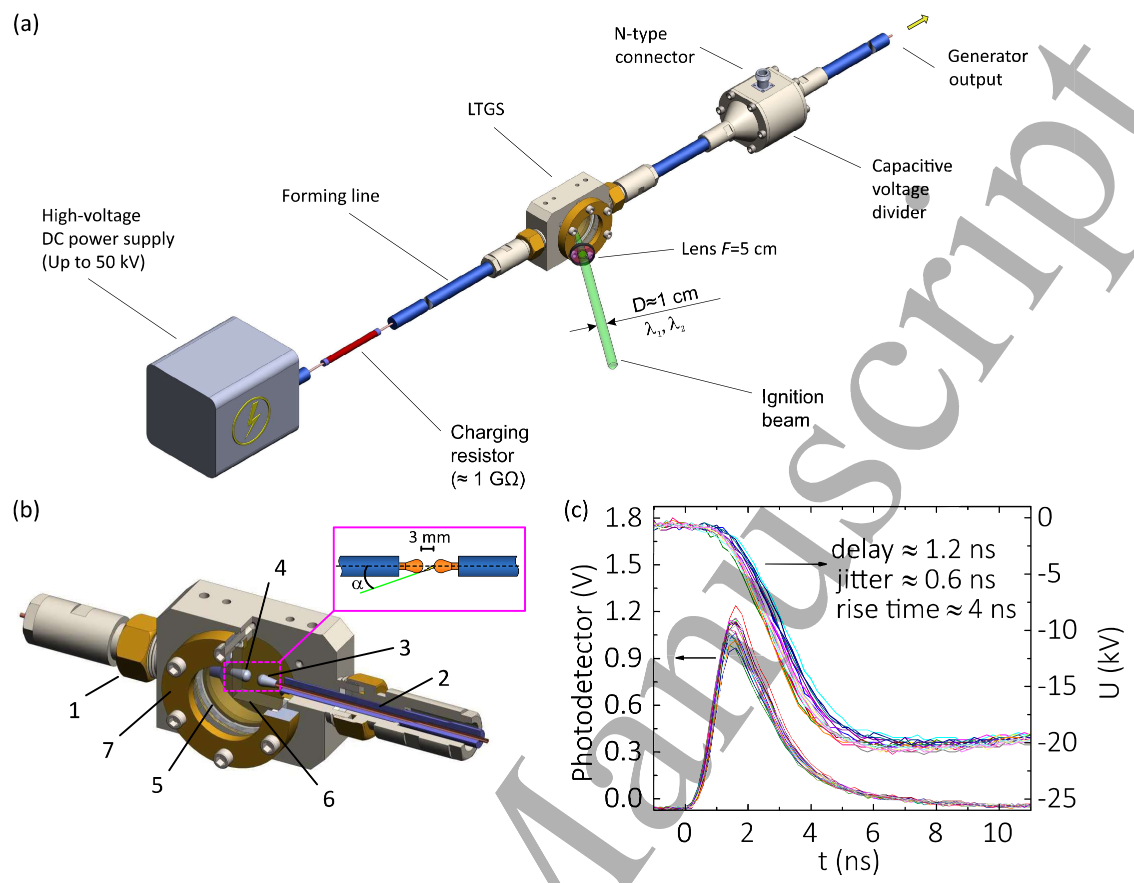

FIG. 1. (a) Scheme of the setup. (b) Design of the Laser-Triggered Gas Switch: *1*–cable holder, *2*–high-voltage cable, *3*–cathode, *4*–anode, *5*–rubber sealing gasket, *6*–glass window, *7*–brass clamping flange. Inset shows the top view of the ignited gap. (c) Typical photo-detector signals and fronts of high-voltage pulses obtained at $U_0 \approx 40$ kV, $Q \approx 20$ mJ, and $\alpha \approx 40°$ for 20 successive triggering events.

surement accuracy (≈ 0.3 ns). Here the LTGS precise operation with the shortest delay was achieved when a plasma filament almost connecting the electrodes was initiated. Such regime is close to the ignition along the gap axis widely used in practice, see in[14–21]. Remarkably, at $\alpha \approx 40°$, $U_0 \approx 45$ kV, and $Q \approx 75$ mJ, almost "synchronous" operation of about five identical LTGSs electrically isolated from each other and from the trigger source can be achieved, with the LTGSs being similar in design to that in Fig. 1(b). Such LTGSs can be further employed in a multi-channel high-current switcher or used for shaping current and voltage pulses. With increasing Δ at $Q \approx 75$ mJ and $U_0 \approx 45$ kV, the delay rises by ≈ 5 ns, whereas the jitter is still < 1 ns, see Fig. 4. Moreover, with $\alpha \sim 40°$–$60°$, the LTGS delay can be tuned within ~ 0.1–10 ns with jitter $\lesssim 1$ ns with decreasing the ignition beam energy to ~ 15 mJ.

The same applies to the variation of the charging voltage at fixed ignition beam energy $Q \approx 75$ mJ (Fig. 3). Here the ignition angle range $\alpha \sim 40°$–$60°$ also allows the delay variation within ~ 0.1–10 ns with almost subnanosecond jitter. Remarkably, for the charging voltage $U_0 \sim 30$–50 kV, a small variation of the amplitude (~ 15–25 kV) of the generated high-voltage pulse can be achieved with the jitter below several nanoseconds. In this regard, the dependences of the delay and jitter on charging voltage U_0 and ignition beam energy Q in Figs. 3 and 4 are mutually complementary and characterize the capabilities of the developed LTGS.

The variation of the ignition beam energy and ignition angle results in a small change in the rise time of the generated high-voltage pulse (inset in Fig. 4 (b)). The rise time was defined as the time interval between the 0.1 and 0.9 levels of the registered voltage signal. With $\alpha \approx 40°$ ($\Delta \approx 0.5$ mm), $Q \approx 75$ mJ, and $U_0 \approx 45$ kV, the rise time was ≈ 2.9 ns and changed little on average with decreasing the ignition beam energy. In contrast to this, with $\alpha > 40°$, $Q \approx 75$ mJ, and $U_0 \approx 45$ kV, the rise time raised to ≈ 4.5 ns and, with decreasing the ignition beam energy, dropped then to ≈ 3 ns. Here the length of the resultant spark channel was close to the shortest distance between the electrodes. Such behavior of the rise time can be related to the change in the inductance of the spark gap, which is governed by the geometry of

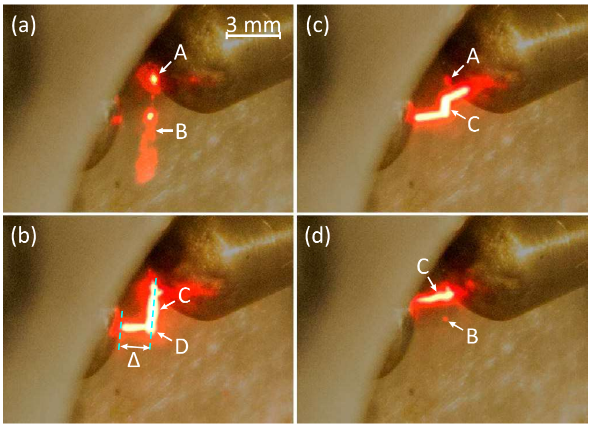

FIG. 2. Integral images of glows in the gap recorded along the ignition beam direction; the ignition angle is $\alpha \approx 60°$. Panel (a) demonstrates the characteristic laser spark initiated by a 80 mJ laser beam before applying a high voltage. Panels (b), (c), and (d) illustrate the resultant spark channels initiated in the gap by ≈ 75 mJ (b), ≈ 15 mJ (c), and ≈ 3 mJ (d) laser beams obtained at $U_0 \approx 45$ kV; A–beam arrival region, B–laser sparks, C–resultant spark channels, D–point where the spark channel sharply turns towards the anode, Δ is the distance from the region with the laser spark to the anode. The cathode is on the right, and the anode is on the left.

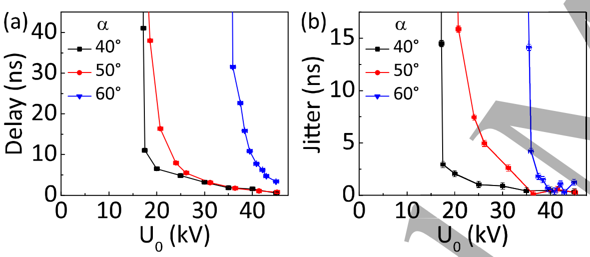

FIG. 3. Dependences of delay (a) and jitter (b) on charging voltage U_0 obtained for ignition angles $\alpha \approx 40°$, $50°$, and $60°$ at the ignition beam energy $Q \approx 75$ mJ.

the resultant spark channel, see Fig. 2.

In conclusion – We created a Laser-Triggered Gas Switch with a fairly simple and compact design with its breakdown delay tunable within ~ 0.1–10 ns with $\lesssim 1$ ns jitter, which was achieved by just adjusting the spark gap ignition angle. The proposed approach to tuning the switching characteristics of the LTGS without changing the discharge medium parameters provides the most efficient and the simplest way to tune the device characteristics while preserving the advantages (low jitter and small delay, or possibility of achieving the desired relation between jitter and delay) of the other well-known methods (variation of the charging voltage or ignition beam energy, etc.). We have demonstrated that, combined with variation of the ignition beam energy and charging voltage, variation of the spark gap ignition angle provides superior control over the gap switching characteristics. The possibility of achieving such control, when there is no need for creating an LTGS with the axial gap ignition (such designs are complicated, their implementation is time-consuming and cost-ineffective, and their optical ignition system is harder to adjust), makes the proposed simple and compact switch highly promising for numerous applied tasks of nanosecond and picosecond high-current electronics as well as for numerous purposes of academic research, e.g., for studying fast plasma formation processes during discharges in gaseous or liquid media. We also suppose that the proposed approach to the LTGS control can be improved with the employment of other gas mixtures at higher pressures.

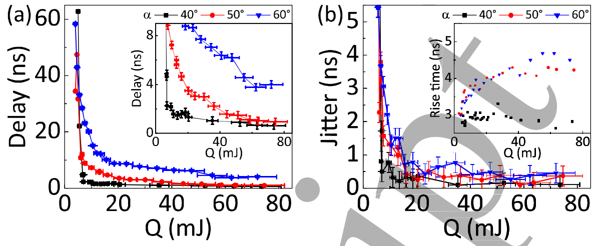

FIG. 4. Dependences of delay (a) and jitter (b) on ignition beam energy Q obtained at the charging voltage $U_0 \approx 45$ kV for ignition angles $\alpha \approx 40°$, $50°$, and $60°$. Insets: (a) region of small delays, (b) rise time of the generated high-voltage pulse vs Q.

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