Discharge initiation by a laser pulse in a vacuum gap

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Abstract. Laser-induced discharge within a vacuum gap of few millimeters between electrodes is experimentally studied. The discharge is triggered by 1064 nm Nd:YAG laser pulses with intensities varied from $10^7$ W/cm$^2$ to $10^9$ W/cm$^2$ on the surface of target electrode. The current formation time dependences from both the gap length and the residual gas pressure at a fixed electrode voltage were determined. Residual gas pressure varied from $10^{-6}$ to $10^{-2}$ torr, and voltage varied from 100 V to 5 kV. The dependences of current formation time on the laser pulse intensity and the voltage difference on the electrodes of different polarity are presented. The laser intensity thresholds for discharge are determined in our experimental conditions. We also performed atomistic and hydrodynamics modeling of laser heating and evaporation of metal from electrode surface. The experimental and modeling results are used for development of qualitative mechanism of ionization and charge multiplication processes in metal vapor.

1. Introduction

With the advent of small laser systems there was a widespread scientific and industrial interest in development of electrophysical installations and devices based on the optic triggering. Use of laser pulse for discharge triggering allows for producing the pulsed discharge in short time intervals with small time jitter, which is widely used in operation timing of various units of power-pulse systems.

One of the most significant advantages of optically triggered switches over those with electrically triggered switches is a galvanic isolation of switched and control circuits [1]. In addition, the optic triggering allows to achieve the more stable time characteristics of the devices, including time delay [2].

The development of fiber-optic systems for optical radiation transportation has made it possible to appreciably simplify and expand the laser light use in application tasks. With regard to the switches, the use of fiber-optic laser pulse transportation allows both to separate the electrical laser power supply system from the discharge gap for long distances and to avoid long, tedious adjustments [3, 4].

However, the laser pulse sources with intensity more than $10^9$ W/cm$^2$ cannot be used for fiber-optic transportation, in particular, because of the technological difficulties of fiber working surface treatment.

At present, such processes as discharge ignition and laser pulse interaction with substance are studied in detail. However, the process of discharge triggering in vacuum by optical radiation in the applied external field hasn’t been studied in details. So, a detailed study of the mechanism of discharge triggering in vacuum by optical radiation of moderate intensity of about $10^8$ W/cm$^2$ is an actual task for development of laser-triggered switches not only with flexible, but also with spatial system of laser pulse transportation, since decrease in operating radiation intensity leads to lower energy consumption and smaller weight and dimensions of laser.
Our aim is to develop a qualitative mechanism of ionization and charge multiplication processes in metal vapors using experimental data and numerical simulation. In this study we found that such mechanism leading to current switching in a laser-triggered discharge gap can be summarized as follows. First, the laser pulse heating of target cathode results in intensive evaporation of metal into the gap. Because the heating takes several nanoseconds the vapor flow from cathode may generate a spatial gas pressure profile ranging from very low pressures to many atmospheres. Second, the ionization coefficient is too small in metal vapor at pressures exceeding several tens of torr, it is reasonable to distinguish between a high-pressure zone 1 with a negligible ionization rate and a low-pressure zone 2 where electron impact ionization can efficiently produce new electrons and ions, as illustrated by figure 1. Thus, the low-pressure zone 2 may work as a source of plasma, which then is accelerated greatly into vacuum toward an anode, see the high-speed plasma zone 3 in figure 1.

![Figure 1. Mechanism of laser-produced evaporation from cathode and discharge initiation in the vacuum gap.](image)

2. Experimental Assembly
The experimental setup was designed for carrying out the study, see the block diagram in figure 2. Optical radiation was generated by a pulsed solid-state laser (1). The laser beam coming to the beam splitter (3) is divided into two parts. The first part (less than 1%) came to the light sensor (2), following which the oscilloscope (10) detects a laser pulse caused by a photoelectron current. The second (rest) part passing through the anode (5) hole focuses on the target cathode (6) surface, that causes intense heating and evaporation of the cathode material. The laser plasma is generated in the spark gap, which leads to gap shorting and further discharge of the capacitor (7). The oscilloscope (10) registers a pulse of electric current.

The electrode system is in a sealed housing in vacuum, and it includes the plane-parallel cathode and anode made of titanium. Discharge gap is 1 mm length. The anode has a hole of 1 mm diameter for laser pulse. Lasers with wavelength of 1064 nm and pulse durations of 2 ns and 12 ns were used for the experiment. Intensity of laser pulse on the target varied from $4 \times 10^7$ W/cm$^2$ to $2 \times 10^{10}$ W/cm$^2$. Current pulse duration and height were 5 μs and 60 A, respectively. Capacitor voltage was 3 kV. In experiments the current formation time (CFT) is used for analyzing current time parameters. CFT is determined as a time interval between the onset of rising laser intensity at half of laser pulse height and 0.1 of maximum of the generated current pulse. Instead of the CFT, the maximum current time (MCT) is used in the theoretical discussion section. MCT is defined as a time interval between the maxima of laser pulse and current pulse. Typically, MCT is longer than CFT by ~ 80 – 100 ns.
3. Experiment Results

Figure 3 illustrates the current formation time (CFT) as function of laser pulse intensity for three residual gas pressures of $10^{-5}$, $10^{-4}$, and $10^{-3}$ torr. Dependencies behave in the same way and demonstrate the weak linear increase of CFT at decreasing the laser pulse intensity, which becomes exponential at intensities less than $2 \times 10^8$ W/cm². Conditionally, the dependence can be divided into two parts: with rapid and slow increase of CFT time. In the part with a rapid increase of CFT time the triggering processes are probabilistic. The lower is laser pulse intensity, the less discharge gap triggering probability. Thus, in the experiments carried out with minimum values of laser pulse intensity, the triggering probability was reduced to 5%. Hence, only 5% of laser pulses triggered the discharge of RC-circuit capacitor. The discharge was not observed at lower intensities. It is important to note that the time interval between laser pulses was more than 5 seconds and the different quantity of laser pulses were obtained between discharges when the laser pulse intensity was small.

Figure 4 illustrates the experimentally obtained CFT times for different pressures of residual gases in the spark gap. As it can be seen from the plot, not only CFT time increases with decreasing the laser pulse intensity, but also the jitter is determined as the standard deviation of CFT time. Thus, dispersion of CFT times at laser pulse intensity of $5.7 \times 10^8$ W/cm² does not exceed 1 ns, but it is already more than 10 ns at the intensity of $4.3 \times 10^7$ W/cm². That is, where the laser pulse intensity decreases by 3 times, the jitter increases by more than an order of magnitude. CFT time within the studied intervals, taking into account the error, does not depend on the pressure of residual gas in the spark gap, which
excludes its influence on the ionization and generation of the current pulse observed in our experiments.

![Graph showing CF times at residual gas pressures in the spark gap.](image1)

**Figure 4.** CF times at residual gas pressures in the spark gap.

Figure 5 demonstrates the obtained CF times for a wider range of intensities. When intensities are less than $1.4 \times 10^7$ W/cm$^2$ the dependence form is the same as that in figure 3. However, when intensities are higher than $3.6 \times 10^9$ W/cm$^2$ the CF time dramatically falls from 13 ns to 5 ns and then to 2.8 ns. This peculiarity indicates a fundamental difference in the mechanisms of breakdown triggering at intensities of about $10^8$W/cm$^2$ and $10^9$W/cm$^2$.

According to figure 5 the minimum intensity of laser pulse required to initiate discharge is $4.4 \times 10^7$ W/cm$^2$. However, when the intensities are less than $2 \times 10^8$ W/cm$^2$, the current pulse rise edge jump is observed on the oscilloscope records (at some level relative to the amplitude the current decreases sharply, and then again begins to increase).

![Graph showing CF times in a wide range of laser pulse intensities.](image2)

**Figure 5.** CF times in a wide range of laser pulse intensities.

For discharge triggered by optical radiation with intensity of about $10^8$ W/cm$^2$ in vacuum, the experimentally obtained CF time as function of voltage between the electrodes does not depend on the electric field strength in the spark gap (see figure 6). When triggering the laser-induced plasma on the grounded electrode (cathode triggering) with optical radiation of $7 \times 10^8$ W/cm$^2$ intensity, the CF time remains at level of 13 ± 1 ns in the voltage range from 250 V to 5 kV. However, a completely different situation is in case of anode triggering (when electrode polarities are changed). Thus, CF time increase follows the increase of voltage from 250 V to 3.5 kV, and it remains at 23 ± 1 ns level for voltages more than 3.5 kV.
Figure 6. CF times for voltages in gap.

Figure 7 shows the CF time as function of the gap length. The gap length varied in the range from 0.9 mm to 5.3 mm. The laser pulse intensity for experiment was $7 \times 10^8$ W/cm$^2$. As we can see from the plot, the dependence is linear for whole measurement range and described by equation: $t [\text{ns}] \approx 3.8d[\text{mm}] + 8.4$, where $t$ is CFT, and $d$ is gap length. Thus, the medium for commutation is formed for about 8 ns (at laser pulse duration at half-height of 2 ns) and further propagates with speed of $2.6 \times 10^5$ m/s. It is likely, that gap is shortened only after laser plasma ions reach the anode. Indeed, in case of maximum gap length used for the experiment, the electrons affected by electric field of $5.6 \times 10^5$ V/m will reach the anode in less than 0.3 ns, that does not correspond to the measured CFT. The CFT independence on the electric field strength also indicates that the discharge is triggered specifically by plasma, since the condition of quasi-neutrality is fulfilled. Moreover, when pressure is changed by three orders of magnitude, the CFT does not change within the error limits, that mean that the residual gas in the gap does not participate in the commutation process, that is, does not serve as a source of charged particles. Residual gas can participate in discharge triggering only at intensities greater than $2 \times 10^9$ W/cm$^2$, where there is a transition from one triggering mechanism to another (figure 5).

In [5] the authors used Langmuir probe methods to study the leading group rate of laser plasma ions generated on the Si, Fe, Cr, Mn, and Sn targets. The results showed that the ion rates in a rising edge of the laser-plasma flame have the following dependence:

$$V \sim M^{-3/2},$$

where $M$ is an atomic weight of the element. The data are given for laser pulse intensity of about $10^9$ W/cm$^2$ and wavelength of 1064 nm. The leading group ion rates were measured on the Sn, Cr, and Si targets and equal to $4.5 \times 10^4$, $7 \times 10^4$, and $9 \times 10^4$ m/sec, respectively. Proceeding from the data provided the ion rates on the rising edge of laser-plasma flame on the Ti target can be estimated. It equals to $7 \times 10^4$ m/s that is 4 times less than the commutation rate.

Figure 7. CF times for the gap lengths.
The ion spectra of titanium laser-induced plasma for different intensities of 1064 nm laser light is studied in [6]. Authors detected the Ti$^{1+}$, Ti$^{2+}$, Ti$^{3+}$, and Ti$^{4+}$ titanium ions with maximum energy of 3 keV, which corresponds to the ion rate of $1.1 \times 10^5$ m/s.

It is important to note that both studies did not provide information on accounting the pulse-to-pulse changes of plasma composition. The probe diagnostics of the laser-induced plasma on the titanium target showed that parameters of current to the probe differ for different pulses. So, for example, the amplitude of electron current has decreased by 40 percent for 100 shots. This effect is explained by increase of cavern surface area (due to target material evaporation) in the focus region that leads to decrease of laser pulse intensity and change of laser-induced plasma parameters. In experiments, where discharge is generated after target exposure by laser pulse, this effect is significantly reduced, since the cavern surface is «smoothed» when discharge is ignited.

4. Calculation of Laser Flame Characteristics
The laser flame characteristics were calculated using one-dimensional equation system of laser flame mathematical model, which consists of:

- one-temperature equations of radiation plasmodynamics;
- one-dimensional equations of radiation transportation;
- one-dimensional equations that determine the spatial position of contact boundary.

The 2D calculations performed before showed that the laser flame radius considerably exceeds its longitudinal size, so the main calculation series was carried out using one-dimensional mathematical model.

1D calculation was carried out for laser pulse intensity of $1 \times 10^9$ W/cm$^2$, which corresponds to the steady and stable discharge gap operation. Figures 8 and 9 demonstrate this calculation results. The vapor temperature for this calculation increased to $T = 7$ K. But ionization rate is relatively low ($\leq 0.01$).

Thus, the laser pulse effect on the electrode (without taking into account the external electric field) is resolved to small heating of electrode erosion products and accompanied by slight increase of their ionization rate. At this, the erosion products move with velocity of $V \approx 3$ km/s and can reach the anode surface in $t = 3 \times 10^{-6}$ s.

![Figure 8](image_url)

Figure 8. Spatial distribution of $a)$ pressure $P$ (atm), $b)$ temperature $T$ (K) at the time $t = 9.3$ ns.
5. Discharge Triggering Mechanism

According to calculations of laser pulse absorption in the metal, the cathode surface temperature can reach several thousand degrees. An intense metal evaporation occurs that leads to formation of gas cloud moving to the anode. The question arises – are the discharge rise and gap breakdown possible?

Figure 10 illustrates the examples of aluminum, copper, and titanium saturated vapor pressure increase with temperature, which are plotted using the experimental data for relatively low temperatures [7]. The choice of these materials was caused by literature and experimental data on their physical properties.

Figure 10. Aluminum, copper, and titanium saturated vapor pressure dependence on $a)$ reciprocal temperature, and $b)$ temperature. Signs indicate the experimental data [7], straight lines indicate their approximations. Temperature coefficients in the fitting formulas $T=35.9$, $39.4$, and $56.8$ kK correspond to the cohesive energy of these metals.

Given that the gas discharge physics formulas [8] usually use not density but pressure of gas under normal conditions, we need to bring $p(T)$ to this gas pressure at room temperature for subsequent estimations. So, for example, the pressure of $1300$ atm at $T=6000$ K shall be reduced to
1300 atm × (300 K / 6000 K) = 65 atm that corresponds to the same density of ideal gas at 300 K temperature.

The charge multiplication in the gas by collision ionization with electrons accelerated in the electric field is determined by Townsend ionization coefficient $\alpha$. Simple empirical formulas are often used for it [8]:

$$\frac{\alpha}{p} = A \exp \left( -B \left( \frac{p}{E} \right)^{-1/2} - C \frac{p}{E} \right),$$ (2)

where $A, B, C$ are fitting coefficients for gas in question.

Unfortunately, the Townsend coefficient is well known for conventional gases at normal temperature, such as noble gases and atmospheric gases, but there are incomparably less experimental and/or calculated data for metal vapors. We were able to find only the copper vapor calculation data in [9]. Therefore, further we will consider only copper, assuming that the results for other metals shall be the same in order of magnitude.

Figure 11 (a) shows an important difference between the metal vapors and noble gas vapors, namely, very small number of new charges produced by electron passing the unit of length in a sufficiently dense gas. This is caused by presence of very low-lying excited states (compared to noble gases, where the energy of excited states is close to the ionization energy) and excitation cross-sections large in comparison with ionization cross-sections. Taking into account the high pressure of several atmospheres of metal vapor (calculated in section above) evaporated by laser pulse in a relatively small applied field, this peculiarity puts an end to developing the electric breakdown of high pressure evaporated vapor layer.

Indeed, let’s consider the breakdown condition for layer of thickness $h$ filled with gas under pressure $p$. The breeding coefficient for electrons generated by a single electron on the way $h$ will be

$$\gamma (\exp(\alpha h) - 1),$$ (3)

where $\gamma$ is a coefficient of secondary electron emission when the ion reaches the cathode surface. The coefficient standard values $\gamma = 0.05 - 0.2$ for a variety of singly charged (monovalent) ions [8]. It should be noted that secondary electron emission caused by photons is very small due to the low photon energy, and the total photon-induced current is less than thermionic current in spite of the large photon flow.
Then the charge number increase is possible if $\gamma(\exp(ah) - 1) > 1$, and the critical condition for this is:

$$ah = \ln (1 + 1/\gamma)$$

(4)

The solution of this equation determines the Paschen curves (dependence of breakdown voltage on the gas cloud thickness $h$). Figure 11 (b) demonstrates solution of this equation with ionization coefficient for copper from figure 11 (a) at $\gamma = 0.1$.

According to figure 11 (b) the vapor layer breakdown is not possible at layer thickness of 1 mm under standard field strength and gas pressure conditions. In fact, for pressures higher than the 1 atm used for calculation the breakdown voltage becomes even higher. This completely eliminates the possibility of charge multiplication (avalanche) and dense gas layer breakdown.

Next, we consider the mechanism, where the cathode itself can be a source of current pulse charge observed in the experiment. In that case the possible mechanism can be the arc striking at sufficient thermoelectronic (or combined with termoautoelectronic) emission from a hot cathode. However, the thermoelectronic emission alone is not enough to produce arcing discharge, the fields of about $10^6 - 10^7$ V/cm are required to reduce the work function and increase the autoelectronic (field) emission of the electrons.

To create such field on a plane cathode, the positive spatial charge should be accumulated near the cathode, that leads to formation of thin cathode layer $\sim 10$-100 nm. The ions in this layer are accelerated to the cathode and heat it so that the electron yield is within the range of 2 to 9 per a ion.

To estimate the time of required positive charge accumulation in the near cathode layer caused by thermoautoelectron flow passed, we integrated the rate of charge density accumulation:

$$\frac{dn}{dt} = \alpha j_T / e$$

(5)

where $e$ is an electron charge, $\alpha = 1$ cm$^{-1}$ is very high ionization coefficient taken for copper dense vapors (see figure 11 (a)), and $j_T$ is a thermoautoelectron emission current density. Figure 12 (a) shows that even under the most optimistic conditions, the low coefficient of metal vapor ionization prevents from arc striking until 1000 nanoseconds, that contradicts the experimental data.

![Figure 12. a) Current by field-enhanced thermionic emission (red line and left axis) dependence on the cathode temperature and time required for typical cathode layer formation with charge density of $10^{19}$ cm$^{-3}$ for arc striking (blue curve and right axis). b) Paschen curve for copper (as in figure 10 (b)) for breakdown field strength $E_p$ depending on the thickness $d$ of vapor layer with pressure $p$. Intersections with horizontal dashed lines give the minimum thicknesses $h$, at which the effective electron multiplication in the field with a constant strength of 30 kV/cm begins.](image-url)
Thus, all mechanisms that require ionization of dense metal vapors, such as gas breakdown and arc striking above plane hot cathode, do not correspond the experiment results. Therefore, it is necessary to consider the generation of sufficiently large current directly from the cathode, namely, the mechanisms of flat surface instability and occurrence of cones (protrusions), on which a sufficient increase in the field voltage can be expected, which provides the necessary amplification of the autoelectronic current.

Such increase is possible in case of Tonks-Frenkel instability development [10], at which the Taylor cones with jets at the top grow on the cathode surface [11].

The instability develops when negative ponderomotive pressure generated by electric field exceeds the pressure of capillary forces and the pressure of gravity force in hemispherical protrusion (in CGS system):

\[
\frac{E^2}{8\pi} > \frac{\gamma}{\lambda} + \frac{\rho g \lambda}{2}
\]

where \(\gamma\) is a surface tension and \(\lambda/2\) is a surface curvature radius. The electric field strength (and hence the density of surface charges) in this approximate formula is considered as independent on the surface curvature.

Exact dispersion equation for gravity-capillary waves in presence of electric field can be written as [10]:

\[
\omega^2 = \frac{k}{\rho} \left( \gamma k^2 + \rho g - \frac{E^2}{4\pi} k \right)
\]

Then, the critical (cutoff) field, at which \(\omega^2 = 0\), for developing the instability of short capillary waves, if gravitation is ignored, will be:

\[
E_{cr} = \sqrt{\frac{4\pi \gamma k}{\rho}}
\]

The representative time of this instability development from the metal surface perturbed by thermal fluctuations was determined in Ref. [12] as a representative time of growing autocorrelation function of the surface shape:

\[
\tau = 6\sqrt{3\pi^3 \rho \gamma / E^3}
\]

Thus, for our field of \(E = 3 [MV/m] = 100.07 [CGS]\) this formula applied to aluminum with a typical surface tension \(\gamma = 500\) dyne/cm gives \(\tau = 0.047\) seconds.

In order to obtain the experimental maximum current time of \(~100\) ns, we need to apply the field \(E_{cr} = 188\) MV/m, which is \(~2\) orders of magnitude greater than that in our case.

Thus, none of the above mechanisms of the current pulse generation in the system under consideration can give the pulse arrival time comparable with the experimental one in order of magnitude.

The main reason for considered mechanism failures is the assumption that the layer of evaporating metal has a high pressure of several or more atmospheres. As shown above, the electrons cannot multiply in such vapor at required rate.

In fact, the high-pressure vapor profiles obtained in the previous section should be preceded by wide low-pressure vapor regions, which arose during metal evaporation as it was heated by laser pulse. In this case, the breakdown of expanding low pressure layer is possible as well as the current pulse formation for an acceptable time of about 100 ns as shown in figure 12 (b). As in figure 11 (b), a Paschen curve for copper is shown here as well as the horizontal \(E/p\) lines corresponding to the pressure selected at the experimental field strength of \(E = 30\) kV/cm. Had the steam filled the cell without pressure change, the condition for avalanches formation would have took place at the intersection of these horizontal lines with Paschen curve, i.e. when the vapor layer has reached the thickness \(h\) shown in the figure 12 (b). Taking into account that the time of vapor layer formation should be as low as 100 ns, and the rate of vaporized gas expansion reaches \(1 \sim 2\) km/s = \(1 \sim 2\) \(\mu m/ns\),
as will be shown below, the maximum layer thickness should be of no more than \( h \approx 200 \mu m = 0.2 \) mm. The copper vapor layer with a pressure difference from 6 to 40 torr meets this condition.

Formation of such low-pressure gas layer during evaporation of metal into vacuum is highly non-equilibrium process, which is required an atomistic method for its simulation. To study the early stage of metal evaporation during laser heating and expansion velocity of low-pressure gas layer, we carried out a trial calculation of \( 20 \times 100 \times 100 \) nm aluminum film using molecular dynamics method. The vacuum area extended along the evaporation axis \( x \) by 1000 nm from the right and left film surfaces. Periodical boundary conditions were laid off along the \( y \) and \( z \) axes. The number of atoms at the calculation beginning was 11.6 million. The vaporized atoms that reached the left or right boundary of calculation region at \( x = \pm 1000 \) nm were rejected.

The process of 20 nm aluminum film heating was controlled by a Langevin thermostat with target temperature of 5000 K and typical heating time of 0.5 ns. In order not to interfere with the evaporation process, the thermostat was used only in the 5 nm central layer of the film. Therefore, the temperature of near-surface layers of the film was slightly lower due to the cooling by evaporation. For more exact compliance with the experimental conditions, the complex task of calculation of metal surface temperature dynamic under laser exposure should be independently solved with any other program.

Figure 13 (a) shows that the noticeable atom evaporation starts only in 1 ns after heating, when the film temperature reaches about 2700 K. At this, the gas flow accelerates to 2 km/s. However, the low-pressure region from 6 to 40 torr will expand with 0.8 km/s only, because the position of 40 torr moves with velocity about 1.2 km/s, see the sketch shown in figure 1. This region with the best conditions for electron multiplication is shown by dashed horizontal lines in figure 13 (b), which demonstrates the dynamics of evaporating aluminum pressure profiles.

Thus, we assume that the main source of charge in the observed current pulse is the charge multiplication in the leading low-density vapor layer (atom concentration is \( 10^{15}-10^{18} \) cm\(^{-3} \) order of magnitude, and the ionization coefficient reaches its maximum value at such concentration) located
before the denser vapor layer. Proceeding from the preliminary calculation results, this mechanism is able to provide a typical current increase matching the experiment data in order of magnitude.

6. Conclusion

We developed a qualitative mechanism of ionization and charge multiplication processes in the metal vapors, which triggers the current switching in vacuum optically-controlled spark gaps. The laser pulse affecting the target cathode heats the electrode erosion products to a temperature of about thousands of Kelvin. Above the target surface, there is a high-pressure vapor expanding into a vacuum with a wide low-pressure vapor region at the front, which occurred during metal evaporation while heating by laser pulse. The low pressure metal vapors are ionized under external field exposure. Then, the laser-plasma flame moves to another electrode at front velocity of $2.6 \times 10^5$ m/s and shorts the spark gap a few nanoseconds later, which leads to current switching.

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