A limit value of the volume discharge ignition frequency in dense gases

B A Kozlov
Department of Electronic Instruments, Ryazan State Radiotechnical University, 59/1 Gagarin Str., Ryazan, 390005, Russia
E-mail: kozlov.qe.ryazan@mail.ru

Abstract. There is deduced analytical expression for maximum value of the volume discharge ignition frequency in dense gases. That expression indicates the way for achieve maximal values of pulse repetition rates in CO₂-lasers at atmospheric and super-atmospheric pressures. The increasing of pulse repetition rates is connected with sectioning of main discharge gap and excitation of volume discharge in each section from separate pulse pumping generator. This work is devoted to describing of constructions and main characteristics of some types compact pulse generators with amplitude of voltage pulses up to 200 kV, rise-times about 10 nanoseconds and pulse energy per pulse up to 20 J. For reduction of rise-time of high-voltage pulses were used spark-discharge two electrodes commutators (sharpeners) at working pressures up to 100 atm.

1. Introduction
Currently some laser technologies require CO₂-laser pulses with an energy of 10–50 mJ and duration of 10–20 nanoseconds at pulse repetition rates of up to 10–20 kHz. Existing types of TEA-CO₂ lasers operate at pulse repetition rates up to 1 kHz or less. Numerous research results have shown that the pulse repetition rate in this type of lasers depends from many processes both in the gaseous medium and on the working surfaces of the electrodes. Their combined effect leads to the transformation of a volume discharge into a local one, which is not suitable for pumping purposes. For ignition of a volume discharge in dense gases (one atmosphere and above) in the pulse-periodical mode a forced renewal of the gas mixture in the interelectrode gap in the pause between pulses is used. This is done so that the formation of a volume discharge takes place in a gas in which there are no “traces” of various kinds of inhomogeneities initiated by the previous discharge pulse. Inhomogeneities can be caused by complete or incomplete weakly accurate spark channels. The maximum ignition frequency of the volume discharge in these circumstances is determined by the gas flow rate and the width of the electrodes along the flow. However, the effective removal of various inhomogeneities in the gaseous medium does not affect the elimination of thermal inhomogeneities on the surface of the electrodes.

In this work we solved the problem of establishing the relationship between the limiting values of the ignition frequency of a volume discharge and the main electrophysical parameters of a pulsed pumping generator, the composition of the gaseous medium and the thermophysical parameters of the electrode materials under conditions when an effective change of the gas mixture occurs in the interelectrode gap between discharge pulses.
2. Theoretical consideration

The frequency of a volume discharge ignition in dense gases is limited by the time during which the inhomogeneities of density, chemical composition and temperature of gas are equalized, as well as temperature inhomogeneities on the surface of electrodes [1–3]. Otherwise there is an “accumulation” of local heterogeneity and the subsequent degeneration in this area of the discharge gap of a volume discharge into a high-current spark or arc channel through which all current flows.

The currently developed methods of suppressing acoustic and thermal inhomogeneities in gaseous media in pulse-periodical TEA-CO$_2$ lasers, as well as multiple updating of the gaseous medium in the discharge gap and in the near-electrode regions in the pause between pulses, eliminate or at least noticeably weaken the possibility of localization volume discharge under the influence of causes unrelated to the local heating of the electrodes.

The time required for the alignment of thermal inhomogeneities on the surface of the electrodes depends only on the geometric dimensions of the heterogeneity and the thermophysical properties of the material of the electrodes [4, 5]:

$$\Delta t = b^2 / a,$$  \hspace{1cm} (1)

$b$ – is the characteristic size of the thermal heterogeneity on the surface of the electrode; $a$ – is the coefficient of temperature conductivity of the electrode material.

The maximum frequency of ignition of a volume discharge in this case, in accordance with (1), is determined by the ratio:

$$F_{\text{MAX}} = 1 / \Delta t = a / b^2.$$  \hspace{1cm} (2)

For typical values of $b \approx 0.1$ cm, corresponding to the diameter of the spark channel, and the thermal conductivity coefficient $a \approx 1$ cm$^2$·s$^{-1}$, the maximum ignition frequency of the volume discharge is limited to the value of $F_{\text{MAX}} \approx 100$ Hz [4].

The value of thermal inhomogeneity used in these estimates on the electrode surface is determined by the transverse dimensions of the spark channel that initiates it, and generally depends on the value of the charge passed through this channel and the chemical composition and pressure of the gas medium [6–8].

In order to obtain a more complete expression for the limiting value of the ignition frequency of the volume discharge in dense gases, a one-dimensional theoretical model schematically presented in figure 1. It is based on the following assumptions:

- Thermal inhomogeneity on the electrode surface is caused by a complete or incomplete spark channel and is described by a "Π"-shaped function with a temperature of $T_0$ within the inhomogeneity;
- The geometric dimensions of the thermal inhomogeneity on the electrode surface coincide with the diameter of the spark channel;
- The diameter of the spark channel varies according to the law [8]:

$$d = k \times (T_0) \times \tau_{\text{SD}}^{1/2},$$  \hspace{1cm} (3)

$\tau_{\text{SD}}$ – is the duration of the spark discharge current; $k$ – is a constant determined by the type of gas and its pressure (for air at atmospheric pressure constant $k$ has a value of $10^5$ cm$^2$·s$^{-1/2}$ [8].

The expression (3) is an analytical approximation of the spark channel diameter for pulse durations of spark current $\tau_{\text{ld}} \leq 80$ ns and currents up to 5 kA [8]. A similar expression for the diameter of the spark channel occurs for time intervals up to several microseconds [6].

The model allows to establish the relationship between the cooling time of local thermal inhomogeneity on the electrode surface and of the spark discharge current duration.

For the initial temperature distribution in the form of a step function in the interval $x_1$–$x_2$, the temperature change $T$ over time $t$ is determined by the equation [5]:
\[ T(x,t) = \frac{T_0}{2a(\pi t)^{3/2}} \cdot \int_{-x_2}^{x_1} \left[ \exp\left(-\left(x - \zeta\right)^2 / 4a^2t\right) d\zeta \right], \tag{4} \]

\( T_0 \) – is the initial temperature in the area of locally heated spot; \( a \) – coefficient of temperature conductivity; \( \zeta \) – is the current coordinate.

For the central part of the locally heated spot, the time dependence of the temperature can be converted to the form:

\[ F_{\text{MAX}} = 1 / \Delta t = \left(4 \cdot 0.36\right)^2 \cdot a / d_0^2 = A \cdot a / k^2 \cdot \tau_{\text{id}}, \tag{5} \]

\( A \) – is the error function; \( d_0 = x_2 - x_1 \) – initial size of the locally heated spot.

By specifying the duration of the spark discharge current, the values of the spark channel diameter were calculated on the basis of the equation (3), and then by (5) – the corresponding cooling times of local thermal inhomogeneities. The results of these calculations for nickel and copper electrodes are shown in figure 2. For characteristic durations of local discharge currents in hundreds of nanoseconds, the equalization times of thermal inhomogeneities reach values of tens and hundreds of milliseconds, which, according to (2), limits the ignition frequency of the volume discharge at a level of several tens of hertz. To achieve pulse repetition rates, several kilohertz of the duration of local discharge currents should not exceed tens of nanoseconds, and the electrodes should be made from materials with a high temperature conductivity coefficient.
\[ F_{MAX} = 1 / \Delta t = (4 \cdot 0.36)^2 \cdot a / a_0^2 = A \cdot a / k \cdot \tau_{sd}. \]  

The value of \( \Delta t \) in this expression was defined as the time during which \( T / T_0 = A / A_0 \approx 0.36 \).

The duration of the spark channel current \( \tau_{SD} \) can be calculated from the value of the attenuation increment of electrical oscillations in the discharge circuit formed by the series connection of the capacitive storage device \( C \) of the pulse generator, inductance \( L \) of the discharge circuit and the ohmic resistance of the spark channel \( R_{SD} \) as [10]:

\[ t = 2L / R_{sd}. \]  

The value of \( R_{SD} \) in this expression depends on the amount of charge that flows through the spark channel [6–8]. Using the known relationship between the length of the spark channel and the amount of charge was obtained as:

\[ R_{sd} = l_{AC} \cdot h / Q = l_{AC} \cdot h / C \cdot U, \]  

\( l_{AC} \) – is the length of the spark channel (in this case, the magnitude of the interelectrode gap \( A \rightarrow C \) for ignition of the volume discharge); \( Q \) – is the amount of charge passing through the spark channel; \( C \) and \( U \) – is the capacitance of the storage capacitor and the voltage of its charge; \( h \) – is an empirical constant that has values in the range of \( 5 \times 10^{-5} < h < 5 \times 10^{-4} \Omega \cdot \text{cm}^{-1} \) [7].

Smaller values of the constant \( h \) refer to \( \text{CO}_2 \)-laser mixtures enriched with helium, intermediate – to nitrogen and air, and large – to argon [7].

The ohmic resistance of the spark channel in a \( \text{CO}_2 \)-laser mixture enriched with helium (for example, \( \text{CO}_2 : \text{N}_2 : \text{He} = 1 : 1 : 8 \)) for typical values of \( C = 10 \text{nF}, U_C = 20 \text{kV} \) and \( l_{AC} = 1 \text{cm} \) corresponds to a \( R_{SD} \) of \( \approx 0.25 \text{Ohm} \).

By equation (6) the value of the spark discharge current duration through its ohmic resistance and the inductance of the discharge circuit the following expression can be obtained for the ignition frequency of the volume discharge:

\[ F_{MAX} = \left( a / 2k^2 \right) \cdot \left( h \cdot l_{AC} \right) \cdot \left( a / L \cdot C \cdot U \right). \]  

The resulting expression establishes a connection between the maximum ignition frequency of the volume discharge in dense gases with the chemical composition of the working mixture (constants \( k \) and \( h \)), the value of the discharge gap \( l_{AC} \), the thermal properties of the electrode material (temperature conductivity coefficient \( a \)) and the main electrical parameters of the pulse generator and the entire discharge circuit – the capacitance of the storage capacitor \( C \), its charge voltage \( U \) and the inductance of the entire discharge circuit \( L \) (including the inductance of the switch).

For a certain gas composition, the value of the interelectrode gap and the known electrode material, the equation (9) can be presented in a more compact form:

\[ F_{MAX} = B \cdot a / \left( L_h \cdot C \cdot U \right). \]  

For the interelectrode gap \( l_{AC} = 1 \text{cm}, \) electrodes made of copper and a gas mixture with a high content of carbon dioxide and nitrogen, as well as for air at atmospheric pressure, the constant “\( B \)” has a value of \( \approx 10^{-8} \text{ H} \cdot \text{C} \cdot \text{cm}^{-2} \).

As follows from (10), high values of the ignition frequency of the volume discharge can be achieved at very low values of the electrophysical parameters of the pulse generator connected to the electrodes for ignition of the volume discharge – the inductance of the discharge circuit, the capacitance of the storage capacitor and the voltage of its charge. It is obvious that if the volume of gas excited in the plasma of the volume discharge is maintained, the decrease in the capacitance of the storage capacitor and the voltage of its charge will lead to a noticeable decrease in the pump energy density, the gain of the active medium and, accordingly, to an unacceptable decrease in the laser radiation energy (up to the failure of generation).
High values of the ignition frequency of the volume discharge in dense gases with preservation of the volume of the excited gas and the required density of the energy dissipated in it can be achieved provided that the main discharge gap is partitioned and the volume discharges are simultaneously ignited in each of the sections from autonomous pulse generators. In this case, the education in some sections of the local spark channel (which is always inevitable!) due to the small geometric dimensions of the local thermal inhomogeneity on the electrode surface, the inhomogeneity cooling will occur very quickly and the conditions for the process of "accumulation" of the local thermal inhomogeneity will not be fulfilled (or at least will be greatly weakened).

3. Results of experimental studies
On the figure 3 the scheme of the pulse generator by means of which simultaneous excitation of volume discharges in three gaps is given. Each discharge gap was formed by a pair of profiled (by the method of Bruce) electrode length of 8 cm. As the material for electrode manufacturing were used copper and aluminium. The geometric dimensions of each gap for the ignition of the volume discharge was \( V_i = 5 \times 1.2 \times 0.6 \text{ cm}^3 \). All three gaps were located along a single "optical" axis. To exclude the breakdown between the electrode pairs, they were isolated from each other by dielectric plates on the voltage exceeding the breakdown voltage of the individual discharge gap. The initial ionization of the gas mixtures was realized by a "single" source of VUV radiation on the basis of successively included spark discharges. The excitation source of primary ionization was established from an independent pulse generator.

![Figure 3. Pulse generator circuit for simultaneous excitation of a volume discharge in three sections: PT1–PT3 – pulse transformers, C1–C3 – storage capacitors, C0 – peaking capacitors, T1–T3 – thyratrons.](image)

High voltage pulses for excitation of volume discharges, as shown in figure 3, were formed by compact and low-inductive pulse transformers. All three pulse transformers were located in the oil tank. As a switch used pulsed hydrogen thyratrons with "duty" discharge type TGI2-500/20. Hard synchronization points the launch of three thyratrons is achieved by applying one of the trigger pulse with amplitude \( U = 1.8 \text{ kV} \) and an additional adjustment of the hydrogen pressure by heating voltage of hydrogen generator. The amplitude of high-voltage pulses reached 45 kV with the duration of the rise-time up to 50 ns. The duration of the volume discharge current at a half of maximum ranged from 45 to 65 ns.

Figure 4 shows the dependences of the maximum ignition frequency of a volume discharge in CO2:N2:He mixtures with the initial chemical composition of 1:1:2 (a), 1:1:4 (b) and 1:1:8 (c) with a total one atmosphere pressure for partitioned (1) gaps, excited from individual generators, and gaps, formed by two electrodes (2) with the same volume being excited. In the latter case, the outputs of the
three pulse generators were combined, which is equivalent to the excitation of a volume discharge in an unseparated discharge gap from a single pulse generator with a total capacitance of the storage capacitor \( C_0 = C_1 + C_2 + C_3 \).

It is seen that an increase in the capacitance of the storage capacitor from 3.3 to 9.9 nF in all the used mixtures leads to a decrease in the ignition rate of the volume discharge in the “not partitioned” gap by \( \approx 3 \) times. The decline in the frequency of ignition of the volume discharge in sectioned intervals is much less. The results obtained also show that the absolute values of the ignition frequency of a volume discharge increase with the transition to gas mixtures with a high content of helium. These results are in apparent contradiction with the expression (9) according to which for CO\(_2\)-laser mixtures with an elevated helium content, the constant \( h \) has a lower absolute value and, accordingly, the value of the ignition frequency of the volume discharge should be less. However, the lack of information about the value of another constant, \( k \), does not allow us to make a final conclusion about the relationship between the ignition frequency of a volume discharge and the concentration of helium in CO\(_2\)-laser mixtures of atmospheric and superatmospheric pressures.

![Figure 4. Dependencies of the maximum frequency of the volume discharge ignition on the total capacity of the storage capacitors for partitioned (1) and non-partitioned (2) discharge gaps for working mixtures with different chemical composition.](image)

The transition from the interelectrode gap \( d_{ac} = 0.8 \text{ cm} \) to gaps with \( d_{ac} = 1.5 \text{ cm} \) and \( d_{ac} = 2.5 \text{ cm} \) leads to an increase in the maximum value of the ignition frequency of the volume discharge. In a mixture with the initial chemical composition CO\(_2\):N\(_2\):He = 1:1:8 maximum value of the pulse repetition rate reaches to 3.5 and 5.5 kHz respectively.

When igniting a volume discharge in the gaps with aluminium electrodes, the maximum values of the pulse repetition frequency were 1.5–1.8 times lower than those achieved using copper electrodes.

A decrease in the ignition frequency of a volume discharge is also caused by an increase in the charge voltage of the storage capacitances and an increase in the inductance of the discharge circuit. In the latter case inductive elements with the known values of they inductances were injected to each discharge circuit.

Studying the conditions for the formation of a volume discharge in a TEA-CO\(_2\) laser with an active zone of \( V_a = 70 \times 2.5 \times 2 \text{ cm}^3 \) and parameters of a pulsed generator \( C_H = 0.05 \text{ \mu F}, \ U_c = 30 \text{ kV}, \ L = 1.5 \text{ \mu H} \) in a pulse-periodic mode showed that the maximum frequency values ignition volume
discharge does not exceed 30–50 Hz. The maximum frequency estimates from (9) and (10) give the value \( F_m \approx 10 \) Hz.

Estimates of the maximum ignition frequency of a volume discharge based on the values of electrophysical parameters of pulse generators given in [11–16], the type of electrode material and the comparison of these values with the maximum values of pulse repetition frequencies achieved in these works differ by 1.2–5 times and confirm the general tendency to increase in frequency ignition of volume discharges in CO₂-laser mixtures of high pressure in the manufacture of electrodes from materials with a high value of the temperature-conductivity coefficient, reducing the capacitance value of the storage capacitor, the voltage of its charge, the decrease in inductance of the discharge circuit and the increase in the anode – cathode gap. It is rationally from the point of view of achieving higher ignition frequencies of a volume discharge to make sectioning of the main discharge gap with excitation of discharges in each section from autonomous pulse generators.

4. Conclusion

An analytical expression is obtained for the limiting value of the frequency of ignition of a volume discharge in dense gases. That expression connects the limiting value of the frequency with the parameters of a pulse generator, the thermophysical properties of the electrode material and the type and pressure of the working gas. The resulting expression explains the impossibility of obtaining relatively “high” (tens and hundreds of hertz) excitation frequencies of a volume discharge in large-scale TEA-CO₂ lasers.

The analysis of the obtained expression shows that the attainment of “high” ignition frequencies for a volume discharge is fundamentally possible only if the discharge gap is partitioned and the volume discharges are simultaneously excited in each section from an autonomous pulse generator.

The validity of the expression obtained is confirmed by numerous studies on the ignition of a volume discharge in “monolithic” and in sectioned discharge gaps, using various interelectrode gaps of different sizes, varying the parameters of the discharge circuit and using different CO₂-laser mixtures.

In the CO₂:N₂:He =1:1:8 working mixture, when using a partitioned discharge gap, the maximum ignition frequency of the volume discharge \( F_{\text{MAX}} = 5 \) kHz with a pump energy density of 150–180 mJ/cm³ was achieved. Under the same conditions without the use of sectioning of the discharge gap, the maximum ignition frequency of the volume discharge at the same pump densities reached 2 kHz.

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