INTERACTION OF LASER RADIATION WITH MATTER

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Interaction of an optical pulsed discharge with a gas: conditions for stable generation and merging of shock waves

V.N. Tishchenko, V.V. Apollonov, G.N. Grachev, A.I. Gulidov, V.I. Zapryagaev, Ya.G. Men'shikov, A.L. Smirnov, A.V. Sobolev

Abstract. **The conditions under which an optical pulsed discharge stably generates periodic shock waves are determined theoretically and experimentally. It is shown that the mechanism of merging shock waves into a low-frequency quasi-stationary wave is operative in various gases (and vapours) in a wide range of laser spark energies. The application of such a wave for increasing the coupling factor in a laser engine is considered.**

Keywords: *laser radiation, optical discharge, shock waves, laser engine*.

1. Introduction

The transformation of repetitively pulsed laser radiation into a low-frequency quasi-stationary wave (QSW) in an optical pulsed discharge (OPD), which was studied for the first time in Ref. [2], is considered in Ref. [1]. Unlike a continuous optical discharge, no physical constraints are imposed on the velocity of OPD propagation in a gas (see below). In contrast to a single laser spark, the shock waves (SWs) generated by an OPD are merged to form a QSW propagating in a preferred direction in the surrounding gas. About 25 % of the laser power is transformed into SWs in an OPD, which may exert a considerable influence on the surrounding medium.

The mechanism of wave merging can be described as follows. Periodic perturbations (e.g., SWs) with an initial velocity exceeding the sound speed C_0 are successively generated in a continuous medium. The velocity V_0 of propagation of the pulsation region is lower than C_0. The SWs combine to form a QSW if the parameters of the pulsations and the medium satisfy the criteria formulated in this study. Depending on the space – time structure of the pulsations, the mechanism manifests itself in the form of effects characterised by a long elevated-pressure region.

V.N. Tishchenko, G.N. Grachev, Ya.G. Men'shikov, A.L. Smirnov Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavrent'eva 13/3, 630090 Novosibirsk, Russia; e-mail: tishenko@mail.nsk.ru;
V.V. Apollonov A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia;
A.I. Gulidov, V.I. Zapryagaev, A.V. Sobolev Institute of Theoretic and Applied Mechanics, Siberian Branch, Russian Academy of Sciences, ul. Institutskaya 4/1, 630090 Novosibirsk, Russia

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This mechanism does not impose any constraints on the type of the medium and the source of pulsations, and its energy (which is important for producing long waves). The QSW can move from the source, which has a point size in a preferred direction. The SWs can also combine during supersonic propagation of an OPD [3], but the length of the combined SW in a direction perpendicular to its front is small. The initial stage of QSW was observed in water upon successive detonation of two charges [4]. In the studies devoted to thermooptical generation of sound in a liquid [5, 6], the SW spectrum could be rearranged by varying the laser pulse repetition rate f^0, or by modulating the high-frequency component by a low-frequency signal of frequency F^0. It was found that the fraction of power at the frequency F^0 is small and proportional to the ratio F^0/f^0. The mechanism of SW formation considered in this work is free from such a constraint; on the contrary, its efficiency increases for large values of f^0 at which waves are merged. For example, it was shown experimentally [7] that the fraction of power at a frequency ~ 36 Hz can be increased several times by increasing f^0 from 100 to ~ 250 kHz.

Like [1, 7, 8], the present study is aimed at studying the interaction between an OPD and a gas medium under the conditions when the wave merging mechanism is manifested. Earlier, we considered the situations when the OPD is stationary or moves along the laser beam axis at a constant relative velocity $M_0 = V_0/C_0 < 1$. The criteria for merging SWs into QSWs in air were determined in Ref. [1].

Here, we determine the conditions under which an OPD stably generates periodic SWs, and study the behaviour of QSWs in various media in a wide energy range of laser sparks. The applicability of QSWs in a laser engine is also substantiated.

Let us briefly discuss the importance of the problems being studied here. It is found experimentally that an OPD exists at any gas velocity $V_0 = 0 - 400$ m s^{-1} if the radiation power exceeds a certain threshold value. However, the transformation of laser radiation into intense interacting SWs is possible only for a certain ratio of the parameters of the OPD and the medium. Hence, it is important to find the conditions for the formation of QSWs in various gases and to determine whether any constraints are imposed on the spark energy. Apart from the acoustics, OPDs and QSWs are also of interest for solving aerospace problems. For example, it was found experimentally [3] that the aerodynamic drag decreases approximately to half its value if an OPD is initiated in front of a body in an incoming supersonic flow. The creation of high-power OPDs sustained by laser or microwave radiation was considered in

Ref. [9]. Increasing the coupling factor J characterising the efficiency of laser radiation application for speeding up an aircraft is one of the main problems in the development of a laser engine [10, 11]. We believe that the value of J can be increased substantially by using QSWs and high-power pulses of duration $\sim 0.1 - 1$ μs with a high pulse repetition rate (tens of kHz). Great progress in the development of such lasers was achieved in Ref. [12] where an average power ~ 10 kW of periodic pulses was attained and the possibility of its further increase was demonstrated.

2. Conditions of stable SW generation

An OPD can propagate in a moving gas with an unchanged focal length, or in a stationary gas with a moving focus of the laser beam. For a low pulse repetition rate f^0, the periodic laser pulses successively produce a chain of isolated sparks on the axis along which the focus moves. As the value of f^0 increases, the sparks form a channel with a high temperature and a low density of decaying laser plasma in the gas [13–15]. Calculations show that the pressure in the sparks levels out under thermal expansion with the surrounding gas pressure over a time $t_c = 0.38 t_d$ (t_d is the dynamic time, see below). Under the conditions of our experiment, $t_c \sim 15 - 20$ μs. By this time, the gas concentration in a spark decreases to $\sim 2\,\%-5\,\%$ of the unperturbed gas concentration N_0. The gas concentration is restored to the level N_0 due to turbulent heat and mass transfer with a characteristic time of $\sim 1 - 2$ ms [14, 15]. It can be assumed that the necessary condition for obtaining a stable OPD and efficient generation of SWs is that the focus of radiation must leave the low-gas-density region over the time $1/f^0$ between two laser pulses. This corresponds to the following relation between OPD parameters: $f^0 < V_0/L_s$ if the spark length L_s is much larger than the spark radius r_0 [13]. For a spherical spark, the minimum distance between the centres of the sparks is determined by the relation [1]:

$$f = t_d f^0 < f_b = 2.5 M_0. \quad (1)$$

The time and distance are normalised to the dynamic time $t_d = R_d/C_0$ and the dynamic radius $R_d = (q/p_0)^{1/3}$ (in metres) respectively, where q is the spark energy (in joules) and p_0 is the unperturbed gas pressure (in pascals). A single spark can be treated as an explosion [16]; for this reason, the quantities t_d and R_d used in the theory of a point explosion can also be applied for describing OPDs. Straight line (*1*) in Fig. 1 shows the dependence of the threshold frequency on M_0; above this line, the focus cannot leave the low-pressure region.

Experiment. Expression (1) was verified in the following experiment. An OPD in stationary argon (in a chamber) or in an argon jet effusing into the atmosphere was produced by 1-μs pulses from a ~ 1.5-kW CO_2 laser. The jet and the radiation propagated in the same direction along the common axis. In this case, the OPD as an SW source is stationary relative to air. The jet was narrow (diameter 3 or 6 mm) and had little effect on SWs passed into air.

The pressure in the SWs was measured with a piezoelectric transducer located at a distance of 5 cm from the OPD on a line passing through the OPD at an angle of 90° to the jet axis. Such a position of the transducer was chosen taking the weakened effect of the background into account. At small distances from the OPD, the background intensity is much lower than the intensity of SWs generated by the OPD. The intensity of laser radiation incident on an OPD and transmitted through it was measured.

We studied the regimes of periodic laser pulses or periodic trains of laser pulses with a repetition rate $f^0 \approx 20 - 120$ kHz. The repetition rate of pulse trains was $F^0 = 1.2$ kHz. Accordingly, the OPD produced periodic SWs or SW trains. The effect of the jet velocity $M_0 = V_0/C_0$ and frequency $f = f^0 t_d$ on the SW generation stability and the efficiency of transformation of laser radiation into SWs were studied.

Figure 1 shows some values of M_0 and f at which the SW pressure was measured. The jet velocity V_0 was varied at a fixed pulse repetition rate f^0, or vice versa. The SW generation efficiency can be estimated from the shape of signals from the piezoelectric transducer (Figs 2 and 3) and the mean SW power (Fig. 4). One can see from the time dependence of pressure that each laser pulse produces SWs in the entire range of parameters being studied. However, SWs are unstable for $f > f_b$; their average power and the efficiency η of transformation of laser radiation into SWs decrease. The SW instability is a consequence of the fact that weaker pressure jumps and, hence, weaker SWs, are produced in a hot gas.

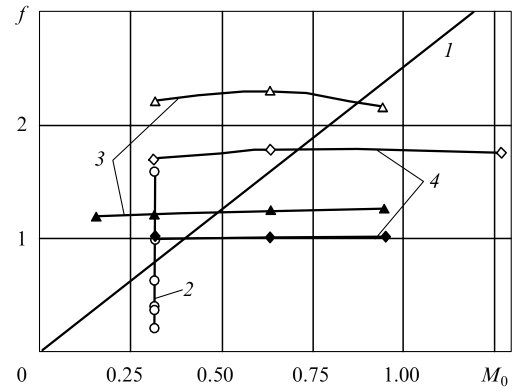

Figure 1. Theoretical dependence (*1*) of the maximum laser pulse repetition rate f on the velocity M_0 of OPD motion [the OPD stably generates SWs in the region below line (*1*)] and experimental values of f and M_0 (symbols for which the SW pressure was measured for the averaged power $W = 1.3$ kW of the absorbed laser radiation, average SW power $W_a = 140$ W, $f^0 = 51$ kHz, $q \approx 25$ mJ (◆); $W = 1.3$ kW, $W_a = 50 - 76$ W, $f^0 = 116$ kHz, $q \approx 11$ mJ (◇); $W = 0.764$ kW, $W_a = 58 - 179$ W, $f^0 = 53.8$ kHz, $q \approx 40$ mJ (▲); $W = 0.35$ kW, $W_a = 26 - 31$ W, $f^0 = 104$ kHz, $q \approx 33$ mJ (△). The experimental points (circles) correspond to variation of f^0 for $V_0 = \mathrm{const}$. The symbols on lines (*2*) and (*4*) correspond to an OPD generating repetitively pulsed SWs, while symbols on line (*3*) correspond to an OPD generating SW trains with a repetition rate $F^0 = 1.2$ kHz.

We found in experiments that OPD burns and efficiently absorbs radiation ($\eta \sim 70\,\%$) in the entire velocity range under study (up to 400 m s^{-1}), including the case of a stationary gas. The value of η differs from 100 % because the breakdown developed over a time of ~ 200 ns and the leading edge of the pulse was partly absorbed. The value of η can be as high as $\sim 90\,\%-95\,\%$ if the pulse has a steep front and its intensity is much higher than the breakdown threshold of the gas. We also considered the limiting case, when periodic laser pulses with a repetition rate $f^0 = 1$ or 30 kHz produced an OPD in stationary argon (under a pressure $p_0 = 1$ atm). Measurements of parameters of

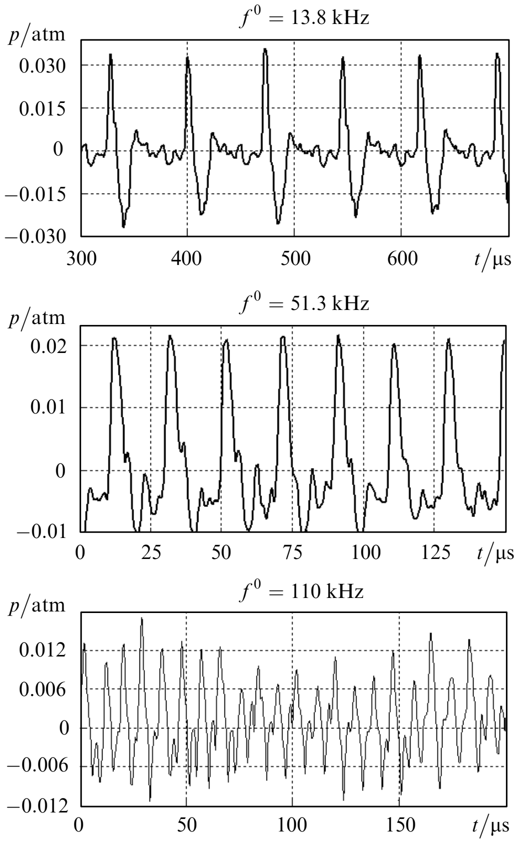

Figure 2. Pressure oscillograms for repetitively pulsed SWs in the case of an OPD burning in a jet ($V_0 = 100$ m s^{-1}) for various frequencies f^0.

incident and transmitted laser radiation show that each laser pulse was absorbed in the OPD.

To confirm this result, we measured emission of the OPD spark plasma using a streak camera. The time sweep was carried out along the spark axis coinciding with the radiation beam and jet axis. Figure 5 shows the streak camera traces obtained for the case when the OPD was

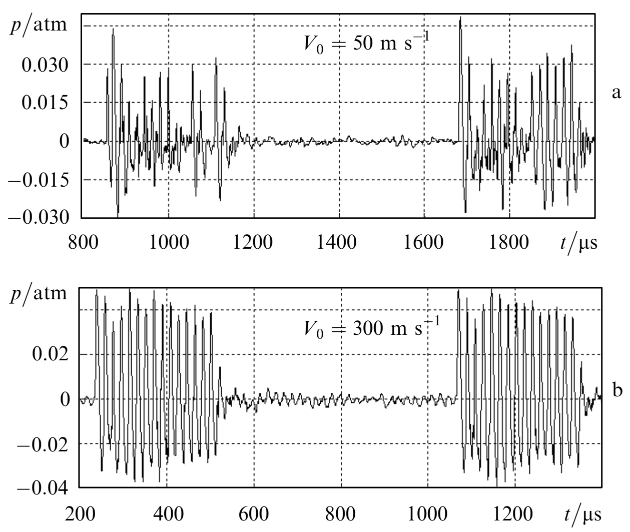

Figure 3. Pressure oscillograms for SW trains for various values of V_0, $W = 610$ W, $W_a = 58$ W, $\eta = 9.5$ % (a) and $W = 764$ W, $W_a = 179$ W, $\eta = 23.4$ % (b). The repetition rate of the trains $F^0 = 1.2$ kHz, the SW repetition rate in trains $f^0 = 53.4$ kHz, the jet diameter is 3 mm.

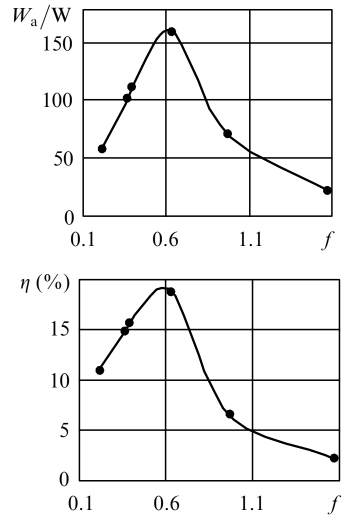

Figure 4. Dependence of the average SW power and the efficiency of transformation of laser radiation absorbed in an OPD into SWs on the dimensionless frequency f. The OPD is produced by periodic laser pulses in a jet propagating at a velocity $V_0 = 100$ m s^{-1}.

produced by periodic laser pulses with a repetition rate $f^0 = 100$ kHz and burned in the jet moving at a low velocity $V_0 = 100$ m s^{-1}. The point with coordinates $f = 2.2$ and $M_0 = 0.316$ in Fig. 1, which lies in the unstable SW generation region, corresponds to these parameters. The following conclusions can be drawn from an analysis of this and other pictures. Each laser pulse produces a spark. The velocity of propagation of the plasma front towards the beam is close to the velocity of light-detonation mode. The position of the focus on the axis is repeated regularly from pulse to pulse. During the pause $\sim 1/f^0 = 10$ μs between the pulses, the gas in the jet moves over a distance $\sim V_0/f^0 = 0.1$ cm, which is much smaller than the spark length $L_s \sim 0.5$ cm. Consequently, sparks are produced in the channel formed by the previous sparks. One can see from Fig. 5 that for $z > 0$ (z is the coordinate along the axis of the radiation beam and the jet), the slope of the luminescence region corresponds to a velocity of the order of 0.5–1 km s^{-1}. This is a manifestation of the effect of plasma acceleration due to its outflow from the high-pressure region to the 'vacuum' channel formed by the moving OPD [17].

Detailed investigations of an OPD burning at low values of V_0 and at $V_0 = 0$ are beyond the scope of this study. We can provide only a qualitative explanation of this process. The necessary condition for the burning of a OPD is that the

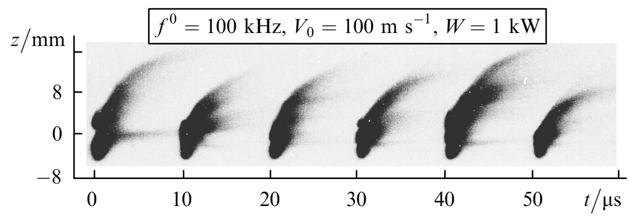

Figure 5. Streak camera traces of the OPD spark plasma emission. The sweep is carried out along the z axis coinciding with the direction of propagation of laser radiation and the jet. The focus is situated at the point $z = 0$.

gas concentration in the focal region should be restored during the pause $1/f^0$ between laser pulses to such a level for which not only the optical breakdown can occur at the focus, but also the conditions are created for the observed light-detonation mode (streak camera traces) of the motion of the plasma front towards the beam. This is a must for efficient absorption of laser radiation. The characteristic time t_1 of turbulent thermal conductivity responsible for the restoration of concentration is of the order of 1 ms [14] (for a single spark). Since $t_1 \ll 1/f^0$, this is not the main mechanism. The most probable reason behind maintaining a fixed gas density and the conditions for OPD burning is the combined action of the convective thermal flow and strong pulsations of the gas concentration in the vicinity of the focal region. We can estimate the gas velocity in the focal region required for replacement of the gas as $\sim 0.5 d_c f^0 \sim 30$ m s^{-1}, where $d_c \sim 0.2 - 0.3$ cm is the spark cavity diameter.

3. Combination of OPD-generated SWs

According to the above hypothesis, the wave combination mechanism operates in various media for all energies and all types of pulsation sources. The following questions are considered in the present study: can we introduce a universal criterion of wave combination for different gases? Does the mechanism hold for an arbitrary pulsation energy? Which constraints on the parameters of the pulsation source (OPD) are imposed due to the requirement of nonlinearity of interaction of the source with the medium? The wave combination mechanism allows us to analyse the results obtained in Refs [1, 7, 8] from a unified point of view.

Certain constraints were employed in the course of our investigations. We considered a stationary OPD or one propagating in a gas at a constant velocity lower than C_0. Equations of gas dynamics in the two-dimensional axisymmetric approximation were solved. For a better generalisation of the results, the spark shape was simulated by a sphere, the velocity (V_0) of the OPD was varied as well as the spark repetition rate and the spark energy ($q = 10^{-3} - 10^3$ J). Calculations were made for air and inert gases xenon, argon and helium, in which the sound speeds are substantially different ($C_0 = 340$, 169, 316 and 965 m s^{-1} respectively). A detailed description of some properties of a QSW in air and the derivation of the criterion for its existence are given in Ref. [1].

QSW formation by a moving OPD. Figure 6 shows a QSW and a part of the field of SWs produced by an OPD. On the whole, the perturbation field has the shape of a sphere expanding with the sound speed C_0. Periodic laser pulses of short duration ($\sim 0.5 - 1$ μs) successively produce laser sparks at the beam focus. The focus moves in the gas and a train of sparks is formed, each spark producing a SW. At subsonic OPD velocities ($M_0 \approx 0.6 - 0.9$), the SWs catch up with one another and produce a region of elevated pressure (QSW) in front of the OPD, which pulsates only at the trailing edge of the QSW in the vicinity of the OPD. Figure 7 shows the pressure distribution in the QSW on the OPD axis. The time and distance along the z axis are normalised to t_d and R_d, respectively. The wave whose length L at the asymptote (more than ~ 100 sparks) is equal to $\sim (10 - 30) R_d$ (i.e., much larger than the compression phase length for a SW from a single spark) is regarded as a low-frequency QSW. For the sake of better visualisation, Figs 6 and 7a show only the initial stage of QSW formation corresponding to $n = 11$ sparks. Figure 7b shows the QSW pressure corresponding to a later instant of time and $n = 280$. The QSW propagates in the same direction as OPD. SWs form a directional field pattern in the opposite direction due to interaction with the plasma trace and the low-pressure phase of the QSW. If the QSW formation conditions are not satisfied, the SW field resembles that produced by a moving acoustic source (Doppler effect).

SW merging conditions. The SWs produced by a moving OPD combine to form a QSW if any two of the three dimensionless parameters ($M_0 = V_0/C_0$, $z_s = z_{sp}/R_d$, $f = f^0 t_d$) satisfy certain requirements (z_{sp} is the separation between the centres of sparks) [1]. The parameters M_0

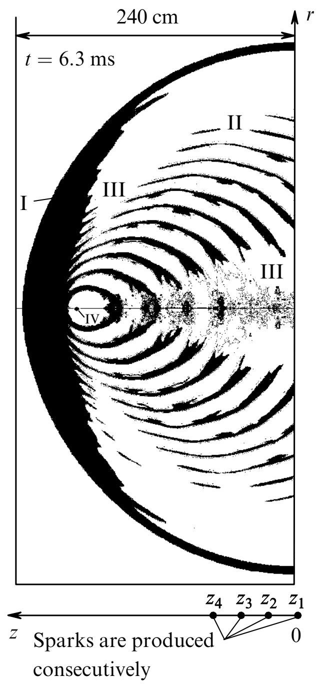

Figure 6. Pressure field in SWs produced by a moving OPD and the diagram of QSW formation. Dark shade corresponds to $p > p_0$, and the light shade to $p \leqslant p_0$ [I – QSW, II – SWs, III – shadow region ($p \sim p_0$), IV – last spark]. The OPD moves from right to left at a velocity $V_0 = 300$ m s^{-1} in air; $p_0 = 1$ atm, $q = 10^3$ J, $f^0 = 2.5$ kHz, $R_d = 21.5$ cm, $t_d = 632.4$ μs, $f = 1.58$, $M_0 = 0.882$.

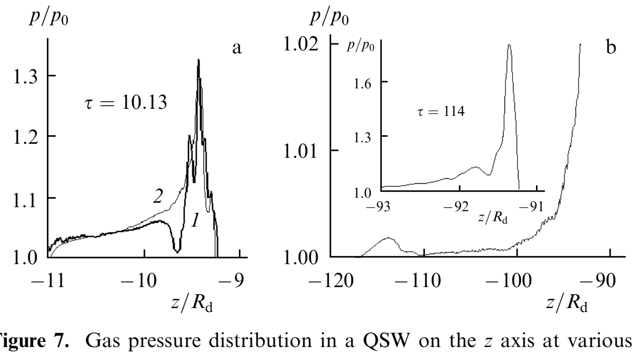

Figure 7. Gas pressure distribution in a QSW on the z axis at various instants $\tau = t/t_d$ in the case of SWs generated (a) in air for $p_0 = 1$ atm, $M_0 = 0.882$, $V_0 = 300$ m s^{-1}, $f = 1.58$, $q = 10^3$ J (*1*) and 10^{-3} J (*2*), and (b) in helium for $p_0 = 1$ atm, $M_0 = 0.8$, $V_0 = 772$ m s^{-1}, $f = 2.46$, $f^0 = 400$ kHz, $q = 0.021$ J. The OPD propagates from right to left.

and z_s are convenient for the case of detonation, while the pair M_0 and f is suitable for an OPD. The parameter M_0 is of special importance since a QSW is formed only for $M_0 < 1$. The conditions for merging of SWs and formation of a QSW can be formulated in terms of M_0 and f:

$$2.5M_0 > f > 5.88(1 - M_0)^{1.5}. \quad (2)$$

This relation can be used to determine the velocity range $0.6 < M_0 < 1$ in which an OPD produces SWs that form a QSW (Fig. 8). The left-hand side of formula (2) corresponds to line (*1*). Below this line, the OPD generates SWs stably. The right-hand side defines the range of parameters M_0 and f [above curve (*2*)] in which the SWs combine to form a QSW. Consequently, a QSW is formed in the region between the curves (*1*) and (*2*), to the right of the point of their intersection. Expression (2) was derived for the air. Because the SW compression phase length (in dimensionless form) depends weakly on the type of the gas, it could be expected that condition (2) is also applicable for other gases. In order to verify this, we carried out a number of calculations whose dimensionless parameters are presented in Fig. 8. The practical significance of inequality (2) is that it makes it possible to determine the OPD parameters required for producing a QSW. Note also that the computation of a single version ($\sim$ 100 sparks) may require several hundred hours of machine time on a modern PC.

If the SW parameters are stable, each point on the M_0, f plane in Fig. 8 corresponds to a large number of combinations of independent dimensional quantities V_0, f^0, q, p_0, ρ_0, and γ_0, where ρ_0, and γ_0 are the gas density and adiabatic exponent. For example, the point + in Fig. 8 corresponds to calculations performed in air for spark energies $q = 10^{-3}$ and 10^3 J. Figure 7a shows the pressure distribution in a

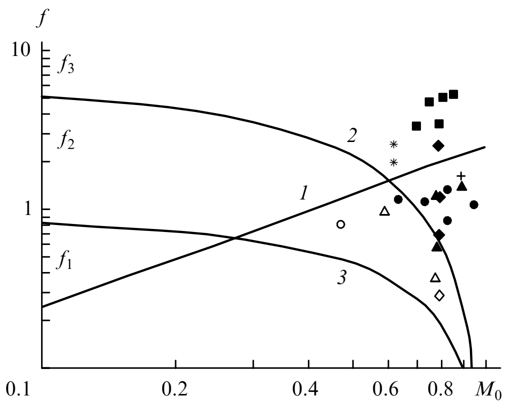

Figure 8. Theoretical dependences of the repetition rate f on the velocity M_0 of OPD motion; the OPD stably generates SWs in the region below line (*1*); SWs produce a QSW above curve (*2*); SWs do not interact with one another below curve (*3*). The OPD produces a QSW on the right of the point of intersection of curves (*1*) and (*2*). The symbol + corresponds to an OPD in air for $q = 10^{-3}$ and 10^3 J (see Figs 6 and 7). Symbol $*$ corresponds to an OPD in air for an unstable energy absorption; ◇, ◆ – He, △, ▲ – xenon, ○, ● – argon, and ■ – water (explosion from two charges) [4]. Dark symbols correspond to the case when SWs produce a QSW, while light symbols correspond to the case when no QSWs are produced. The computational parameters are close to the experimental ones when the average power $W \sim 1.5$ kW, and the spark energy $q = 0.015 - 0.1$ J.

QSW. The criteria of QSW formation are satisfied in the entire energy range $q = 10^{-3} - 10^3$ J investigated by us.

Between curves (*2*) and (*3*), the SW interaction decreases as we move away from curve (*2*) and approach curve (*3*). In this case, the pressure pulsations increase over the entire length of the QSW. SWs do not interact with one another below curve (*3*). Curve (*3*) corresponds to the dependence $f(M_0) = (1 - M_0)(t_d/t_s) \sim 0.81(1 - M_0)$. This expression was obtained from the condition $V_0/f^0 = C_0(1/f^0 - t_s)$, where t_s is the time measured from the beginning of a laser pulse to the instant when an SW is detached completely from the cavity.

For $f > 2.5M_0$ [the region above line (*1*)], the beam focus does not manage to leave the cavity formed by the preceding spark. Here the OPD generates SWs intermittently, which may affect the structure of the QSW even if the wave merging condition is satisfied. Points $*$ in Fig. 8 corresponds to the computations carried out for such a case. Their height is equal to the spread of frequencies f created by the instability of the absorbed energy $\sim 0.015 - 0.034$ J. The dependence of q on gas concentration was taken into consideration during computations. The problem of QSW formation criteria under conditions of instability of OPD parameters has not been studied extensively. However, it is obvious that the spread of dimensional parameters of OPD will correspond to a certain region in Fig. 8, and SWs will form a QSW if this region is situated above curve (*2*). For example, we carried out computations in which the parameters were changed in such a way that the trajectories on the plane of Fig. 8 correspond to a smooth transition from the region above curve (*2*) to the lower part of the plane, and vice versa. In this case, the QSW was found to disintegrate into isolated fragments.

Merging of SWs generated by a stationary OPD. An OPD can produce SWs in a stationary gas also if the constraint imposed by formula (1) on the stability of SW formation is removed. In our experiments and in Refs [7, 8], an OPD burning in a narrow argon jet generated SWs and was stationary relative to the air in which the SWs propagated. In this case, two different values of M_0 should be used. The gas velocity in the jet must satisfy condition (1) for stable generation of SWs by an OPD, which gives

$$M_{01} > 0.4f.$$

The OPD is stationary relative to the air in which the interaction of SWs takes place, hence $M_0 = 0$ on the right-hand side of formula (2). Three frequency regions can be singled out in this case (see Fig. 8):

(1) the region $f_1 < 0.8$, in which SWs do not interact with one another;

(2) the region $0.8 < f_2 < 5.88$, corresponding to the transient region in which SWs combine partially;

(3) the region $f_3 > 5.88$, in which SWs combine.

Figure 2 corresponds to the region of frequencies f_1 (13.8 kHz), while Figs 2 and 3 correspond to the region of frequencies f_2 (51.3 and 53.4 kHz respectively).

Repetitively pulsed SW regime. An OPD is produced by periodic laser pulses. The shape of an SW and its power spectrum are determined by the frequency f [7]. In the f_1 and f_2 frequency regions, the fundamental harmonic of the spectrum corresponds to the pulse repetition rate f. In the f_1 region, the SW power is mainly contained in higher harmonics. This is due to the fact that the duration of an

SW is much shorter than $1/f_1$. In the f_2 region, most of the SW power is concentrated in the first harmonic. Investigations were not made for the f_3 region.

Periodic SW train regime. An OPD is produced by periodic trains of laser radiation with a low repetition rate $F \ll f$. The trains are filled with pulses having a high repetition rate f corresponding to the frequency range f_2 or f_3. The OPD generates SW trains with the same frequencies F and f (see Fig. 3).

In the f_2 region, SWs interact only partly since the SW compression phases do not combine. At frequency $f \approx 2$ ($f^0 \approx 120$ kHz), the spectrum of SW trains contains a high-intensity component at a train repetition rate $F \ll f$ [7]. However, the main part of power in the SW spectrum was at a frequency $\sim f$.

According to calculations made in Ref. [8], SW compression phases in the train combine in the f_3 region. A unified wave (an analogue of a QSW) is produced. If the train duration is much longer than $1/f$, the QSW length is also much larger than the length of the SWs from which it was formed. In this case, the power of periodic trains is mainly concentrated at frequency F. This distinguishes our method from the traditional methods based on low-frequency modulation of a high-frequency acoustic signal, in which the power ratio is very small and proportional to F^0/f^0. We could not generate a QSW in the f_3 region in our experiments since this requires a high-power laser with a pulse repetition rate ~ 250 kHz.

Restrictions on the gas pressure, energy, and spark radius. No restrictions are imposed in expression (2) on the spark energy and other OPD parameters. The restrictions on the most important parameters of the problem can be determined from the condition under which the following mechanism operates: sparks (or another source) should produce SWs. We do not consider here the restrictions associated with the generation of pulsations.

The maximum admissible pulse duration t_{max} can be determined from the condition that the gas remains stationary during the time of energy supply to the gas. In this case, the pressure is maximal. According to the results of our calculations and measurements made in Refs [14, 15], the time t_c corresponding to the fast stage of laser spark propagation is equal to $\sim 0.14 t_d$. Consequently, $t_{max} = 0.1 t_c = 0.014 t_d$. For $q = 1 - 5$ J, we obtain $t_c \approx 9 - 15$ μs and $t_{max} = 0.9 - 1.5$ μs. Let us determine the relation between energy q, spark radius r_0, and unperturbed gas pressure p_0, for which

$$p/p_0 > b_1 \gg 1, \qquad (3)$$

and the mean free path l of particles in the gas is much smaller than the value of $r_*/l = r_* N_0 \sigma > b_2 \sim 100$ (σ is the scattering cross section). It follows from the results of calculations that the value of b_1 must not be smaller than ~ 10; otherwise, the fraction of energy carried away by SWs decreases. Upon thermal expansion of a spark, the gas concentration in it decreases in proportion to $\sim (r_0/R_c)^3$, while the value of l increases. Hence, we should take the cavity radius R_c instead of r_0 for r_* at the final stage of the adiabatic expansion of the spark. In this case, $l \approx (a/p_0)(R_c/r_0)^3$, where the parameter $a \approx a_1(T_0/273\text{ K})$ takes into account the type of the gas ($a_1 = 0.006$ for air) and the temperature dependence of the initial concentration [18]. Using formula (3) and the condition $R_c/l > b_2$, we obtain

$$r_{01} < \frac{q^{1/3}}{p_0^{1/3}}\left[\frac{3(\gamma-1)}{4\pi b_1}\right]^{1/3} \approx 0.17\frac{q^{1/3}}{p_0^{1/3}}, \qquad (4)$$

$$r_{02} > \frac{(ab_2)^{\gamma/(\gamma+1)} q^{1/[3(\gamma+1)]}}{p_0^{(3\gamma+1)/[3(\gamma+1)]}}\left[\frac{3(\gamma-1)}{4\pi}\right]^{1/[3(\gamma+1)]} \approx 0.5\frac{q^{0.152}}{p_0^{0.7}}, \qquad (5)$$

where γ is the adiabatic exponent. The following simplification was made while deriving formula (5): $(r_0/R_c)^3 \ll 1$, which is admissible for $b_1 \sim 10$ or more.

Equating relations (4) and (5), we find the point of their intersection on the r_0, p_0 plane:

$$p_0 = \frac{(ab_2)^{3/2} b_1^{(\gamma+1)/(2\gamma)}}{\sqrt{q}[3(\gamma-1)/(4\pi)]^{1/2}} \approx \frac{20}{\sqrt{q}},$$
$$r_0 = \left[\frac{3(\gamma-1)}{4\pi a b_2}\right]^{1/2} \frac{\sqrt{q}}{b_1^{(3\gamma+1)/(6\gamma)}} \approx 0.063\sqrt{q}. \qquad (6)$$

The parameters in expressions (4)–(6) were taken for air at $T_0 = 300$ K and $\gamma = 1.2$. Formulas (4)–(6) define the region on the r_0, p_0 plane in which a source produces SWs. Of the three quantities q, r_0, p_0 only one is independent. The admissible values for the remaining two quantities are obtained with the help of formulas (4)–(6). Fig. 9 shows the dependences (4) and (5) for $q = 10^{-3}$ and 10^3 J respectively. The requirement of the formation of an SW upon energy absorption is met in the region between curves (*1*) and (*2*) to the right of the point of their intersection with coordinates r_0, p_0.

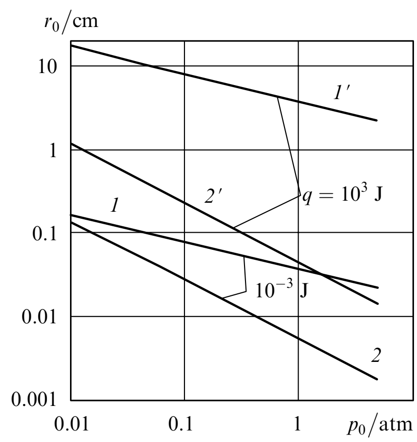

Figure 9. Limiting values of the spark radius r_0 and air pressure p_0 for spark energies $q = 10^{-3}$ and 10^3 J. Curves (*1*), (*1'*) and (*2*), (*2'*) correspond respectively to maximum and minimum values of r_0. The operational range of the wave combination mechanism is bounded by curves (*1*) and (*2*) for a given value of q.

QSW in a laser engine. One of the methods for producing thrust in a laser engine can be described as follows. Periodic laser pulses are incident on a focusing reflector producing periodically repeated laser sparks at the focus. The sparks generate SWs producing an alternating force at the reflector (compression and low-pressure phases in SWs). The coupling factor J characterizing the efficiency of employment of laser radiation is equal to $\sim 100 - 500$ N MW^{-1} (see, for example, [11, 19]).

Here, we suggest that a plane QSW be used for a substantial increase in the value of J. The QSW produces a high constant pressure on a large area of the reflector. A simplified scheme permitting calculations in the 2D axisymmetric approximation can be described as follows. The OPD has the shape of a disc whose plane is perpendicular to the reflector axis and whose radius r_0 is much larger than its length L and smaller than the distance ($\sim 20-50$ cm) between the OPD and the reflector. The SWs generated in the direction of the reflector merge to form a QSW in the region between the OPD and the reflector. Such an idealisation might correspond to a 2D OPD matrix produced synchronously by many beams. Details of the formation of a plane QSW and its model will be presented elsewhere.

We carried out computer simulation to estimate the coupling factor J in the case when a plane QSW is used in a laser engine. The OPD parameters were as follows: $L = 0.5$ cm, $r_0 = 10-15$ cm, and $q \sim 100$ J. The repetition rate f^0 was chosen from the conditions of formation of a plane QSW, which differ from conditions (2). The simulation technique consisted in the following. At the initial stage, the OPD burns in a free gaseous space. After the passage of several hundred microseconds, a QSW is formed in front of the OPD, in which the gas flows at a velocity ~ 300 m s^{-1} in the same direction as the OPD. After this, a wall with which the wave interacts appears on the path of the QSW. Fig. 10 shows the results of computations in air for $p_0 = 0.1$ atm. The range of the high-pressure region increases with time due to the curvature of the leading front of the QSW. After a certain interval of time, an excess pressure $\Delta p = p/p_0 - 1$ is established at the wall, its characteristic value being ~ 2 for a range $R_a \approx (1.5-2)r_0$. For the computation conditions used by us, the coupling factor $J \approx 10\pi R_a 2\Delta p p_0/(qf^0) \approx 1000$ N MW^{-1} (where q is in kJ, f^0 is in kHz, and p_0 is in atm). It follows from our computations that $J \approx 2000$ N MW^{-1} for $p_0 = 1$ atm.

Thus, an OPD can be stationary or move at a high velocity in a gas. However, stable SW generation occurs only for a certain relation between the radiation intensity, laser pulse repetition rate, their filling factor, and the OPD velocity. The OPD generates a QSW in the surrounding space if it is stationary or moves at a subsonic velocity and its parameters satisfy the above conditions. The mechanism of SW merging operates in various media in a wide range of pulsation energies. The results of preliminary investigations show that the efficiency of the laser radiation can be increased substantially when a QSW is used for producing thrust in a laser engine [20, 21].

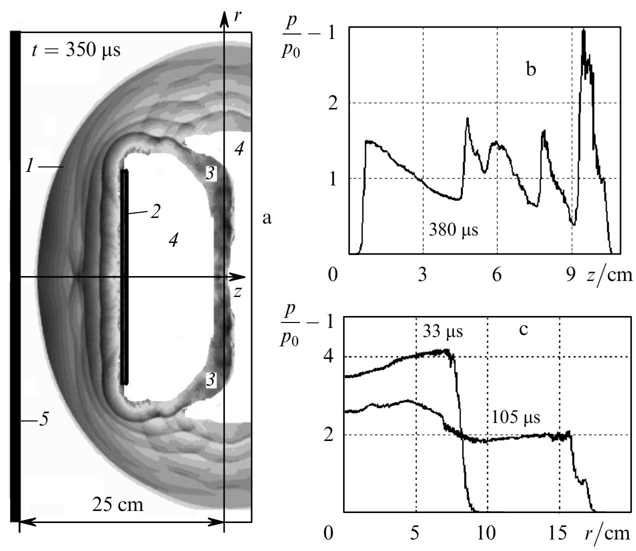

Figure 10. Pressure distribution (a) over radius r in a plane QSW interacting with the wall 350 µs after the initiation of an OPD [(*1*) – QSW; (*2*) – OPD; (*3*) – SWs from the previous pulse; (*4*) – plasma region; (*5*) – wall], (b) over the z axis (z is measured from the wall; the last spark is located at a point $z = 12.8$ cm) and (c) over the wall (time t is measured from the instant of collision of the QSW with the wall at $t = 380$ µs). The OPD propagates in air ($p_0 = 0.1$ atm) from right to left at a velocity ~ 370 m s^{-1}; $r_0 = 12$ cm, $L = 0.5$ cm, $q \approx 100$ J, and $f^0 = 20$ kHz.

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