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Mechanism of shock wave merging in a laser jet engine

V.V. Apollonov, V.N. Tishchenko

***Abstract*. A new approach based on the mechanism of the merging of shock waves generated by an optical pulsating discharge (OPD) is considered for developing laser jet engines (LJE). It is proposed to use high-power repetitively pulsed laser radiation of small duration (150 – 250 ns), energy 20 – 200 J, and a pulse repetition rate of up to 100 kHz for producing an OPD. The formation of an OPD with the help of an array of reflectors allows a manifold increase in the efficiency of laser radiation used for developing an LJE and prevents severe shock loading of the engine, excludes thermal action of laser plasma on the reflector, and decreases the shielding of laser radiation by plasma. Possible values of the LJE thrust are estimated under conditions of the proposed mechanism of merging of shock waves into a quasistationary high-pressure wave.**

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

A laser jet engine (LJE) is proposed for use in projects involving the launching of light spaceships into orbit [1, 2]. With the help of a focusing reflector, repetitively pulsed radiation produces laser sparks (Fig. 1) which, in turn, generate shock waves (SWs). A part of the momentum of the latter is imparted to the spaceship (SS). The radiation parameters proposed for realising an LJE are average power 1 – 3 MW, pulse repetition rate $f \approx 100 - 300$ Hz, energy $q \approx 10$ kJ, pulse duration $t_r = 15 - 30$ μs. These parameters of an LJE are far from optimal. A specific pulse is maximal if a spark is produced in the vicinity of the reflector, but then thermal destruction of its surface and shielding of the emerging radiation by the laser plasma become inevitable. Apart from this, the reflector of the SS is subjected to strong shock loads.

We propose here a new approach to develop an efficient LJE, which is based on the merging of SWs generated by an optical pulsating discharge (OPD) at short radiation pulses with a high pulse repetition rate [3, 4]. In this case, the OPD energy is transformed most efficiently in an LJE into a constant force accelerating the motion of an SS. High-power gas-dynamic lasers, which may generate pulses with $t_r = 150 - 250$ ns and a pulse repetition rate of up to 100 kHz under a continuous pumping of the active medium, offer great promise for the use in the LJE technology [5, 6]. The use of repetitively pulsed lasers is especially efficient if the LJE consists of a reflector array (RA). The model presented below is based on the estimates and numerical simulation in the two-dimensional axisymmetric approximation for thrust pulses generated by the OPD.

Our approach is illustrated in Fig. 1 and can be formulated as follows. Repetitively pulsed laser radiation with a pulse energy $Q \approx 200$ J, $f = 100$ kHz and an average power $W_a \approx 20$ MW [3, 5] is supplied at the input of an RA consisting of $N = 9$ reflectors. Each laser pulse is divided into N parts so that $q \sim Q/N$, $W_n = W_a/N$. It is also possible to use the RA in the form of a ring having a circular central reflector with cylindrical walls, and the remaining eight reflectors constituting the outer part of the ring. All the reflectors have side walls and a spherical end face which receives the mechanical momentum and focuses the laser radiation. An OPD burns in each reflector in a gas jet injected through a nozzle at the centre of the reflector. The jet carries the plasma away from the OPD region, which is necessary for the efficient generation of subsequent SWs. The gas jet velocity exceeds 1 km s^{-1}. Rapidly propagating

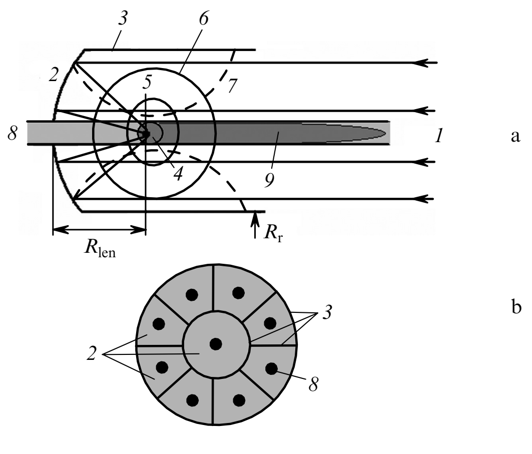

Figure 1. Scheme of the reflector (a) and possible structure of the reflector array (b) in a laser jet engine: (*1*) repetitively pulsed laser radiation; (*2*) end face of the reflector: the collector of radiation and mechanical momentum; (*3*) reflector side wall; (*4*) cavity; (*5*) OPD; (*6*) SW; (*7*) reflected SW; (*8*) gas jet; (*9*) plasma jet.

V.V. Apollonov A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia; e-mail: vapollo@kapella.gpi.ru;
V.N. Tishchenko 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

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SWs generated by the OPD merge to form a quasistationary wave (QSW) which fills the entire volume of the cylinder. The surface of the reflector is subjected to a force $F_a \sim \pi R_r^2 \delta P$ [R_r is the radius of the reflector, $\delta P = (P - P_0) > 0$ is the excess pressure, P_0 being the atmospheric air pressure]. The force F_a is constant (time-independent) if the gas flow is created in the reflector in the same direction as the gas jet, but has a subsonic velocity ~ 300 m s^{-1}. In the opposite case, it becomes necessary to use laser pulse trains with a frequency F, the pulse repetition rate in the trains being $f \gg F$. The duration τ_t of the trains is limited by the time in which the density of air decreases in the reflector. The gas is replaced during the pause $\tau_p \sim a_p R_{len}/C_0$ between the pulse trains (R_{len} is the length of the cylindrical part of the reflector, C_0 is the velocity of light in air, and the coefficient $a_p \approx 1 - 2$).

Reflection at the side walls makes it possible to gather $\sim 1/2$ of the total momentum of the QSW or a solitary SW at the surface of the reflector. The formulation of the problem thus becomes close to the one in the model of a plane explosion in which the specific momentum J_p is maximal. Figure 2 shows the force F_a and the specific momentum J_p calculated for various relations between R_{len} и R_r. Here, in contrast to the conventional schemes, the dependence of J_p on the separation between the OPD and the reflector or on the form of the reflector is not critical. Hence, we can neglect the thermal and impact action of laser plasma on the reflector.

The laser pulse duration t_r is chosen taking into account the following conditions. The fraction of the energy carried away by an SW is maximal if the entire pulse energy is absorbed in the spark during a time shorter than the time $t_e \approx (q/P_0)^{1/3}$ of broadening of the laser spark, where q is the pulse energy in joules and t_e is measured in microseconds. The beam diameter at the reflector is $d_b \approx F_f$ (F_f is the focal length of the reflector and d_b is measured in cm). Hence, the mechanism of optical breakdown (light detonation wave or infrasonic radiation wave) operates over a short distance from the focus (equal to the spark length Z_p) and for a short duration t_r. Beyond this, the radiation may be absorbed in the disintegrating plasma for a certain time t_e. For a constant power W over the pulse duration, the spark length Z_p, the energy q absorbed over it, and the instant t_r of time of decay of the light detonation wave [3] are defined as follows:

$$Z_p \frac{d_b}{F_f} = 0.013 \left(\frac{W}{P_0}\right)^{1/2} \times \left\{1.93 + \ln P_0 + \ln\left[\left(\frac{W}{P_0}\right)^{1/2} (6.3 + \ln P_0)^{3/4}\right]\right\}^{3/4},$$

$$\frac{q}{P_0} \frac{d_b}{F_f} = 0.0014 \left(\frac{W}{P_0}\right)^{3/2} \times \left\{1.93 + \ln P_0 + \ln\left[\left(\frac{W}{P_0}\right)^{1/2} (6.3 + \ln P_0)^{3/4}\right]\right\}^{5/4},$$

$$t_r \frac{d_b}{F_f} = 0.0014 \left(\frac{W}{P_0}\right)^{1/2} \times \left\{1.93 + \ln P_0 + \ln\left[\left(\frac{W}{P_0}\right)^{1/2} (6.3 + \ln P_0)^{3/4}\right]\right\}^{5/4},$$

where W is measured in megawatts. If the value of q is given, W, t_r and Z_p have the following values: $W = 21.7(qd_f/F_f)^{0.617}$, $t_r = 0.0455(qF_f/d_f)^{0.381}$, and $Z_p = 0.194 \times q^{0.352}(F_f/d_f)^{0.648}$ at $P_{01} = 1$ atm; $W = 15(qd_f/F_f)^{0.588}$, $t_r = 0.0665 q^{0.411}(F_f/d_f)^{0.588}$, and $Z_p = 0.357 q^{0.365}(F_f/d_f)^{0.635}$ at $P_{02} = 0.1$ atm. Putting $q = 100$ J and $P_0 = 1$ atm, we obtain $t_r = 0.263$ μs, $W = 372$ MW and $Z_p = 1$ cm. Thus the optimal pulse duration for the LJE is 0.2–0.3 μs.

The mechanism of the merging of SWs in an LJE is operative under the following conditions. SWs leave the jet and merge to form a QSW if $f \geqslant 5.88 C_0/R_d$, which is always observed in the present formulation. The OPD glowing in the gas jet transforms laser radiation into SWs if $V_g \geqslant 86 f^{2/3}(W_n/P_g)^{1/3}$ (i.e., if $V_g > 1.2 \times 10^5$ cm s^{-1}), where V_g is the velocity of the gas jet, P_g is the static gas pressure in the jet in atmospheres, f is measured in hertz, and W_n is the average laser radiation power in megawatts. The conditions of departure of an SW from the jet and demolition of the OPD plasma are met for a jet radius (in cm) $R_g = 0.11(q/P_g)^{1/3} \approx 0.11 q^{1/3}$.

The reflector array must meet the following requirements. Its transverse diameter (~ 1 m) is determined by the conditions of radiation transportation in atmosphere and the prevention of breakdown at the surface of the reflector. The reflector radius is $R_r \approx 0.43 \delta^{1/2}(q/P_{g2})^{1/3}$ and the length of the sidewalls is $L_r \sim 2R_1 \approx 2a_r R_r$ ($a_r = 0.5 - 1$). Here, $\delta \approx 0.03$ is the acceptable fraction of radiation losses at the OPD plasma, and $P_{g2} = 0.1$ atm is the gas pressure in the jet. Note that $R_r/R_d \approx 1$ atm. The force F_a acting on the

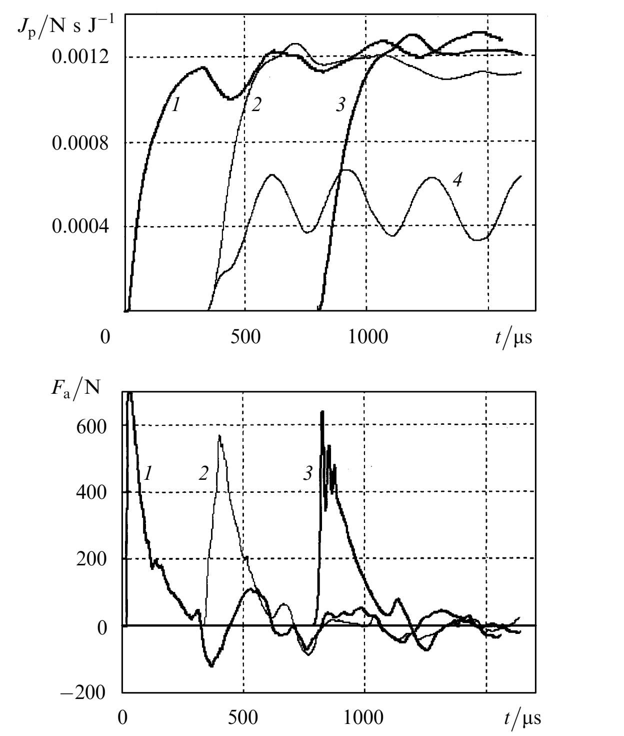

Figure 2. Time dependence of the force F_a and momentum J_p produced by a laser spark with energy $q = 54.8$ J located on the cylinder axis at a distance $R_{len} = 3$ (curve *1*), 16 (curve *2*), and 32 cm (curve *3*), acting on the side wall of the cylinder. Curve (*4*) was obtained for $R_{len} = 16$ cm for the reflector diameter 5 cm. The pulsation of J_p is the result of reflection of SWs at the side walls and their motion over the reflector surface.

reflector surface and the specific force J are defined respectively as follows:

$$F_{\rm a} \approx \frac{81.4 q^{0.67} P_0^{0.45}}{a_{\rm r}^{1.64} P_{\rm g2}^{0.12} \delta^{0.18}}, \quad J \equiv \frac{F_{\rm a}}{W_n} \approx \frac{81.4 \times 10^6 P_0^{0.45}}{a^{1.64} f q^{1/3} P_{\rm g2}^{0.12} \delta^{0.18}},$$

where $F_{\rm a}$ is measured in newtons and J in N MW^{-1}. The RA is subjected to a force $F_{\rm MR} = NF_{\rm a}$.

The duration $\tau_{\rm t}$ of the pulse trains can be estimated as the time in which the first SW in a train covers the distance from OPD to the reflector surface and back (lower estimate): $\tau_{\rm t} = 4.6 \times 10^{-4} q^{1/3}$. Here and below, $\delta = 0.03$, $P_{\rm g2} = 0.1$, $a_{\rm p} = 1$. The ratio of the times $\tau_{\rm p}/\tau_{\rm t} = 0.5 a_{\rm p} \times L_{\rm p}/R_{\rm len}$ and their minimum value is equal to $0.5 a_{\rm p}$. The pulse train frequency for one reflector is $F = 2090/q^{1/3}$, their energy is $q_{\rm t} = 4.63 \times 10^{-4} W_n q^{1/3}$, the average radiation power in the train is $W_{\rm m} = 2W_n/3$, and the average force in the train is $F_{\rm am} \approx 2F_{\rm a}/3$. By optimising the reflector, it is possible to increase $\tau_{\rm t}$ and the energy transformation efficiency of the laser generating the trains.

The parameters of a reflector array and monoreflector in an LJE are compared in Table 1. The average power supplied to the reflector array and to the monoreflector is equal to 20 MW. We did not consider the problems of optimisation of the number N of reflectors or the RA geometry. The RA structure should be chosen by taking into account its use for controlling the flight trajectory and producing the required jet energy and the force of traction of the engine. The array whose data are presented in Table 1 contains eight spherical reflectors with cylindrical walls, and the radiation losses associated with nonoptimal 'packing' are not taken into account. Indices '1' and '2' in the notation correspond to the initial ($P_0 = 1$ atm) and final ($P_0 = 0.1$ atm) LJE modes. Parameters in the first two rows are calculated at various frequencies f for $a_{\rm r} = R_{\rm len}/R_{\rm r} = 0.5$. By reducing $a_{\rm r}$ to extremely low values (~ 0.3), high values of $F_{\rm a}$ can be attained for $f = 100$ kHz (3rd row in Table 1). The use of radiation with a frequency $f > 50$ kHz is hampered in a multireflector LJE – the jet has to move at a very high velocity ($V_{\rm g} \approx 5 - 10$ km s^{-1}). The last two rows show the parameters for an individual reflector as well as an RA as a whole for $f = 100$ kHz ($a_{\rm r} = 0.3$). In this case, the specific force J is much stronger while the jet velocity is lower. The values of $V_{\rm g}$ correspond to an SS velocity range during its acceleration, which facilitates the jet formation. A significant advantage of the RA is the possibility of controlling the flight trajectory with the help of an LJE. For example, the variation of jet parameters in an appropriate reflector can lead to a variation of the traction force in it, thus producing a rotational moment on the RA.

The results of model calculations presented below show that the use of a plane QSW can increase the traction force J considerably and make it possible to impart energy to the supersonic gas flow. Such a wave can be formed under conditions of a point OPD in the presence of side walls and for a subsonic velocity of the OPD moving relative to the gas. Figure 3 shows the gas-dynamic perturbations produced when a OPD burns in a cylinder ($R_{\rm r} \approx 2R_{\rm d}$). One can see that a plane QSW, in which the pressure is constant along the radius and along the direction of motion of the OPD, is formed in front of the point OPD. The specific force corresponding to an excess pressure $\delta P = 0.2$ atm is $J = F_{\rm a}/W_n = 900/0.18 = 5000$ N MW^{-1}. If a point OPD glows in a supersonic flow, the SWs are carried away by the flow [7] and cannot be used for accelerating the SS.

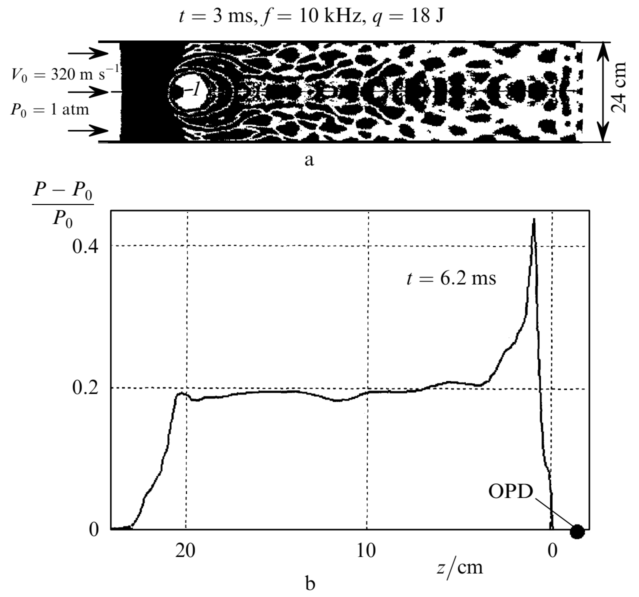

Figure 3. (a) Air pressure field generated during an OPD burning in (*1*) an infinite cylinder of diameter 24 cm for an incident air flow velocity $V_0 = 320$ m s^{-1} and $P_0 = 1$ atm, for a two-dimensional axially symmetric distribution of pressure at the instant $t = 3$ ms after the ignition of the OPD (in the dark regions $P > P_0$); and (b) distribution of excess air pressure in a QSW along the cylinder axis at $t = 6.2$ ms (before ignition of the next spark); the distance along the z axis is measured from the trailing edge of the QSW in the vicinity of the OPD; a plane QSW in which the pressure is independent of the distance from the cylinder axis is formed in front of the OPD.

Constraints on the gas velocity are removed under the conditions of a 'plane' OPD which is an array of synchronously pulsating point OPDs. Since there are no sidewalls between OPDs, the SWs generated by the OPD array merge to form a plane QSW. Calculations show that the pressure in it varies weakly over distances comparable with the characteristic size of the OPD array. Hence, such a wave

Table 1.

LJE type	N	f/kHz	q/J	$R_{\rm r}$/cm	$R_{\rm len}$/cm	$F_{\rm a1}$ (кN)	$F_{\rm a2}$/kN	J_1/N MW^{-1}	J_2/N MW^{-1}	$V_{\rm g1}$/km s^{-1}	$V_{\rm g2}$/km s^{-1}	$R_{\rm g1}$/cm	$R_{\rm g2}$/cm
mono-	1	20	1000	50	25	64	23	2600	930	1.73	3.72	1	2.4
reflector	1	100	200	31	15	21.8	7.73	906	317	5.05	10.88	0.64	1.4
	1	100	200	31	9.5	50.1	17.78	2084	729	5.05	10.88	0.64	1.4
RA	1	100	25	15.5	5	12.5	4.45	4168	1458	2.52	5.44	0.32	0.7
	8	100	200	90	5	100*	35.6*	4168	1458	2.52	5.44	0.32	0.7

*Values for $F_{\rm MR}$.

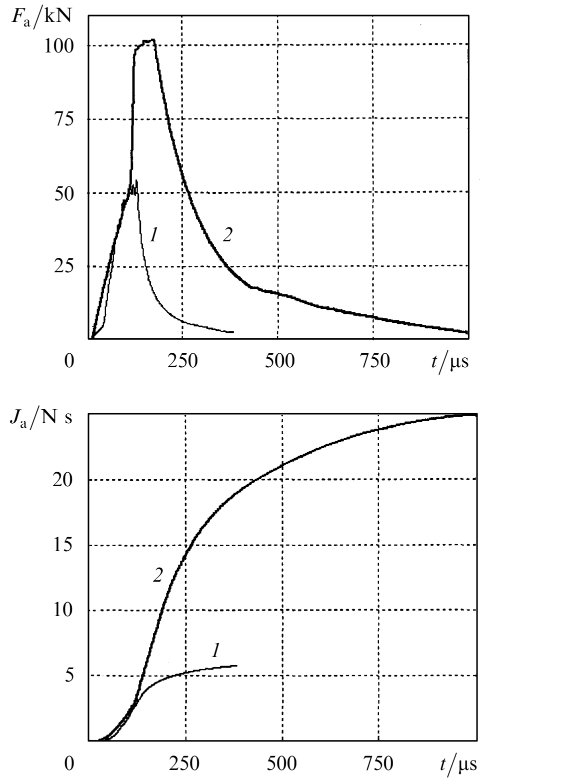

Figure 4. Time dependences of the force F_a and mechanical momentum J_a produced upon collisions of a plane QSW with the end face of the cylinder 350 µs after the ignition of the OPD (curve *1*) and after 1950 µs when the wall is at a distance of 100 cm from the point of start of the OPD (curve *2*) (the time is measured from the instant of collision). The parameters of the two-dimensional OPD are as follows: radius $R_0 = 10$ cm, layer thickness $L = 1$ cm, pulse energy $q = 330$ J, frequency $f = 50$ kHz, velocity of motion along the cylinder axis $V_0 = 480$ m s^{-1}, cylinder radius $R_r = 26$ cm.

can create a continuously operating traction force. Figure 4 shows the force F_a and the mechanical momentum J_a produced by a plane SW upon interaction with the wall. Here the plane OPD moves in a cylinder. Momentum is accumulated in the direction of propagation of the OPD as a result of interaction with the sidewalls. The specific force calculated at half-height $F_a/2$ is $J = 2900$ N MW^{-1}. Figure 5 shows the distributions of pressure and gas velocity in a plane QSW formed during the motion of a plane OPD in infinite space (along the radius) with a supersonic velocity $V_0 = 830$ m s^{-1}. The mass velocity of the gas is approximately equal to V_0, the total pressure P is ~ 6 atm, and the specific traction force is ~ 1300 N MW^{-1}.

Thus, the mechanism of the merging of SWs transforms laser radiation into a plane QSW which produces a steady thrust in the spaceship. Together with an RA and a gas jet, the QSW makes it possible to increase the specific force of traction to a record-high level exceeding 2500 N MW^{-1}, prevent thermal and impact action on the reflector and shielding of the radiation by laser plasma, as well as to use high-power gas-dynamic lasers generating radiation with a pulse repetition rate up to 100 kHz for LJE operation.

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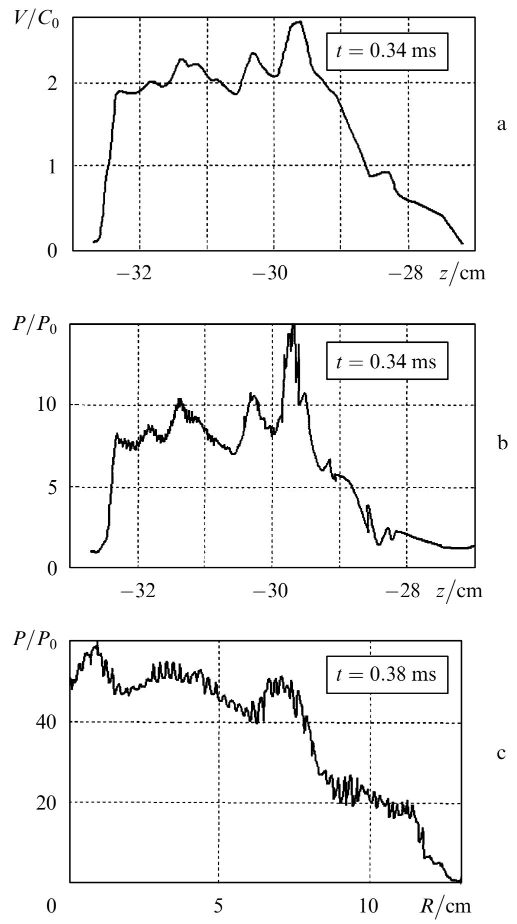

Figure 5. Distribution of the gas velocity and pressure in a plane QSW along the z axis (a, b) and along the radius (c) for the instant of time before (a, b) and during collision (c) of a QSW with the end face of the cylinder. The QSW is produced by a plane OPD moving to the left with a velocity $V_0 = 830$ m s^{-1} under the following conditions: $P_0 = 0.1$ atm, radius $R_0 = 8$ cm, layer thickness $L = 0.5$ cm, $f = 50$ kHz, $q = 140$ J. Measurements along the z axis are made from the point of start of the OPD, and R is measured from the axis.

References

1. Kantrowitz A. *Astronautics and Aeronautics*, **10** (5), 74 (1972).
2. Ageev V.P., Barchukov A.I., Bunkin F.V., Konov V.I., Prokhorov A.M., Silenok A.S., Chapliev N.I. *Kvantovaya Elektron.*, **4**, 2501 (1977) [*Sov. J. Quantum Electron.*, **7**, 1430 (1977)].
3. Apollonov V.V., Tischenko V.N. *Proc. of GCL-High Power Laser Conf.* (Prague: SPIE, 2004).
4. Tishchenko V.N., Apollonov V.V., Grachev G.N., Gulidov A.I., Zapryagaev V.I., Men'shikov Ya.G., Smirnov A.L., Sobolev A.V. *Kvantovaya Elektron.*, **34**, 941 (2004) [*Quantum Electron.*, **34**, 941 (2004)].
5. Apollonov V.V. *III Int. Symp. Beamed Energy Propulsion* (Troy, New-York, 2004).
6. Apollonov V.V., Kijko V.V., Kislov V.I., Suzdal'tsev A.G., Egorov A.B. *Kvantovaya Elektron.*, **33**, 753 (2004) [*Quantum Electron.*, 33, 753 (2004)].
7. Tret'yakov P.K., Garanin A.F., Grachev G.N., Krainev V.L., Ponomarenko A.G., Tishchenko V.N. *Dokl. Ros. Akad. Nauk*, **351**, 339 (1996).