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Laser engine based on the resonance merging of shock waves

V.V. Apollonov, V.N. Tishchenko

***Abstract*. A new approach to the development of a laser jet engine (LJE) is considered which is based on the resonance merging of shock waves generated by an optical pulsed discharge (OPD). The OPD can be produced by using high-power 150–250-ns, 20–200-J laser pulses with a pulse repetition rate of 50–100 kHz. The OPD is formed with the help of a reflector array. This makes it possible to increase the efficiency of utilising laser radiation by a few times, to avoid strong shock loads in the LJE, to eliminate the thermal action of a laser plasma on a reflector, and to reduce the screening of laser radiation by the plasma. The possible thrust of the LJE based on this mechanism is estimated.**

Keywords: *gas-dynamic laser, repetitively pulsed regime, optical pulsed discharge, laser reactive engine.*

1. Introduction

According to the estimates of experts, the market of commercial launchings of satellites for various purposes will increase by 50 % in 2007 compared to 2005. Taking this factor into account, investigations are being performed in the developed countries on the building of rocket engines that are alternative to modern engines operating on chemical fuel, which is often far from being ecologically faultless.

A laser jet engine (LJE) belongs to the most promising rocket engines of a new class. This is the engine of a spacecraft passing the initial part of its trajectory under the action of a long train of laser pulses directed from the Earth.

It is very important that the LJE is considerably more economical than traditional engines operating on chemical fuel. At the initial stage of the flight, the atmospheric air is used as the working substance, and beyond the atmosphere – a small space-borne store of a gas or easily sublimated substance. In this case, the specific cost of freight launching to the outer space can be reduced down to 200–500 USD kg^{-1}, i.e., approximately by two orders of magnitude compared to the cost at present. The possibility of maintaining the parameters of the orbit at a specified level with the help of the laser system used for launching is estimated especially highly.

At present the possibility of building LJEs is being investigated in the developed countries over the world. For example, at present such systems are being developed in the USA within the framework of the Lightcraft project. Thus, Lightcraft Technologies Company has tested successfully a rocket model, which rose to 70 m for 12.7 s under the action of a jet produced by high-power laser radiation. A 10-kW pulsed CO_2 laser was used in experiments. The reactive momentum was produced by carrying out a special polymer material from a concave surface located in the lower part of the rocket irradiated by the laser beam.

As early as 1973, the possibility of building a LJE has been investigated under the supervision of Academician A.M. Prokhorov at the Lebedev Physics Institute, Academy of Science of the USSR. The engine unit operated by irradiating a reflector located at its rear part by a laser beam. The reflector concentrated laser radiation in air, which resulted in a microexplosion and produced the reactive thrust. The tests of reflectors of various types, which served simultaneously as receivers of the incident shock wave providing the thrust, were successful.

Note that all these experiments were performed by using low-power (10 kW) electric-discharge CO_2 lasers, whereas to place various high-tech equipment (for communication, Internet, photomonitoring) in orbit, a considerably higher radiation power is required. For example, to put a satellite of weight 1000 kg in orbit, a laser with the output power of no less than 10 MW is required. At present, such a laser can be only gas-dynamic because only in this case the principles of laser and rocket technologies are close to each other to a great extent. In addition, to avoid the screening of laser radiation by the plasma produced during the engine operation and to increase the laser operation efficiency, the laser should emit short pulses with a high repetition rate.

In the opinion of experts (classical rocket designers), LJEs can be used in low-cost single-stage rockets for the orbital injection of nano- and microsatellites of mass 10–100 kg on which commercial launches will be based in the near future. At the first stage of the flight of such an apparatus at heights up to 30–50 km, the atmospheric air can be used as the working substance and then, before orbital injection, the space-borne store of fuel in amounts not exceeding 15 %–20 % of the satellite weight can be employed.

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The experience in the development of high-power lasers has been accumulated at A.M. Prokhorov General Physics Institute, RAS, at Energomash Research and Production Association, Design Bureau for Chemical Automation, and M.V. Keldysh Research Center. The repetitively pulsed regime in high-power and well-developed cw lasers has been successfully studied in the last years at Eneromash-tekhnika Joint-Stock Company. Researchers at the Institute of Laser Physics, Siberian Branch, RAS and the Institute of Theoretical and Applied Mechanics, Siberian Branch, RAS in collaboration with the General Physics Institute, RAS also have made contributions to the development of the mechanism of efficient utilisation of laser energy in LJEs. This allows these institutions to begin the cooperative experimental development of a superpower repe-titively pulsed gas-dynamic laser, an LJE as a part of a light SiC carrier with the control system, and a ground launching system with the aim of building a global super-broadband, super-high-speed laser communication space Internet network. This complex of works should become an important step preceding the future launchings of superlight satellites to a low circumterrestrial orbit and even launchings of piloted spacecrafts. The realisation of this project will make it possible to build economical reusable LJEs for launching civil and military payloads to outer space.

The main advantage of a new approach is that the source of motion energy and a payload are uncoupled in space, and the start weight of a rocket can be considerably reduced, from 705 tons (Proton rocket) down to a few tons of a payload only. As early as the beginning of the 20th century, great K.E. Tsiolkovsky predicted that future rockets will be launched with the help of electromagnetic waves directed from an external energy source (lasers did not exist at that time).

Three recent symposia devoted to this problem have shown that high-power lasers emitting 150–250-ns pulses at a pulse repetition rate of 50–100 kHz developed in our country attract great interest of foreign researchers. Such operation regime was obtained for a high-power gas-dynamic CO_2 laser and it can be also used in other high-power lasers (HF/DF lasers, diode-pumped Nd : YAG lasers, and chemical oxygen–iodine lasers). At present, a 10–20-MW gas-dynamic laser with a variable temporal structure of radiation is being developed in our country. The efficiency of using laser energy in a new lasing regime was considerably increased, which made is possible to change the estimates of a payload weight from a few tens to hundreds and thousands of kilograms. Note also that the outlook for various applications stimulated investigations in this field in Germany, Japan, England, France, China, Brazil and other countries. It is assumed by almost all researchers involved in these studies that a gas-dynamic laser is the most promising system from the point of view of its scaling based on the rocket technology up the level of a few tens of megawatt and with respect to other important parameters.

By now there exist two directions in the study of the possibility of using laser radiation in aerospace problems: the orbital injection of light spacecrafts [1–9] and the reduction of the aerodynamic resistance of bodies moving at high velocities in the atmosphere [10, 11]. To obtain the jet propulsion, repetitively pulsed radiation from a laser is focused with a reflector near the rear end of a rocket to produce periodic laser sparks. The sparks generate shock waves, which transfer a part of their momentum to the reflector located on this end [1]. The spark repetition rate f is usually limited by the time of the gas change in the reflector and is 100–300 Hz. To achieve the high average radiation power $\bar{W} \sim 20$ MW, it is necessary to use laser pulses of energy $q = \bar{W}/f \sim 200 - 70$ kJ. At low air pressures (at heights above 15 km), a long-lived plasma sphere produced by one pulse occupies almost the entire volume of the reflector (see below), resulting in the screening of the next pulses for ~ 10 ms. The technical difficulty of this method is caused by strong shock loads and mechanical resonances appearing in the rocket construction at high pulse energies q (200 kJ) (approximately 50 g in the trotyl equivalent). In the case of short pulses ($t_r \sim 100 - 200$ ns) in a LJE, $\sim 95\,\%$ of laser pulse energy is absorbed and $\sim 30\,\%$ of the energy is transformed to shock waves. However, the use of high-energy beams with low repetition rates and, hence, with a very high peak power is limited by the optical breakdown in the beam path and on the reflector surface.

We proposed the method to overcome these difficulties, which is based on the use of short laser pulses with a high repetition rate [9, 12] and the resonance merging of shock waves generated by an optical pulsed discharge (OPD) [1–4]. In addition, we showed that the specific thrust can be increased by several times by transforming the radial component of the shock wave to the longitudinal component.

2. Parameters of a spark in the LJE

Laser radiation was focused with a reflector, which can have the form of a hemisphere or paraboloid. Figure 1a presents the typical dimensions of the reflector, focusing region, one spark, and a cavern produced by the spark. The distance F_f between the focal point and reflector should be small ($F_f/R_d < 0.2$), which follows from the condition of the achievement of a high value of the recoil momentum J (R_d is the dynamic radius). To avoid the optical breakdown on the reflector and according to the radiation transport conditions, the beam diameter d_b on the reflector should be large. If the radiation intensity exceeds the optical breakdown threshold, a plasma front propagates toward the laser

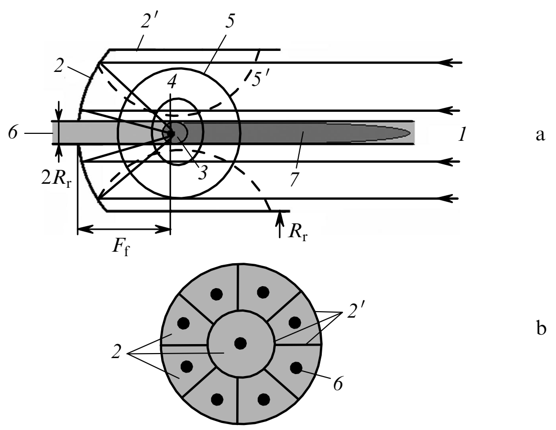

Figure 1. Scheme of a reflector (a) and the possible structure of a reflector array (b) in a laser jet engine: (*1*) repetitively pulsed laser radiation; (*2*) reflector end (receiver of radiation and mechanical momentum); (*2′*) side wall of the reflector; (*3*) cavern; (*4*) optical pulsed discharge; (*5*) shock wave; (*5′*) reflected shock wave; (*6*) gas jet; (*7*) plasma jet.

beam, and the air is heated and ionised due to absorption of laser radiation. Because the radiation intensity in a sharply focused beam rapidly decreases (geometrical factor), the detonation regime of the plasma front propagation is disrupted already at a small distance from the focus. Then, radiation is absorbed in the decaying plasma for some time. The limiting length Z_p of a laser spark in the photodetonation regime is

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

Here, d_b [cm] is the beam diameter on the lens; F_f [cm] is the focal distance; W [MW] is the laser pulse power; and P_0 [atm] is the air pressure. If radiation is switched off at the instant t_r before the quenching of the photodetonation regime, the spark length for a given power is

$$Z_p = 0.67\left(\frac{F_f}{d_b}\right)^{2/5}\left(\frac{W}{P_0}\right)^{1/5} t_r^{3/5}. \quad (2)$$

By equating expressions (1) and (2), we find the instant of time at which the photodetonation regime decays:

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

(t_r is measured in microseconds). The specific laser radiation energy absorbed for the time t_r is

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

These dependences can be approximated in the following form convenient for the use:

For $P_0 = 1$ atm For $P_0 = 0.1$ atm

$$Z_p = 0.0336W^{0.57}F_f/d_f, \qquad Z_p = 0.0667W^{0.62}F_f/d_f, \quad (5)$$

$$t_p = 0.0068W^{0.618}F_f/d_f, \qquad t_p = 0.01W^{0.7}F_f/d_f, \quad (6)$$

$$q = 0.0068W^{1.62}F_f/d_f. \qquad q = 0.01W^{1.7}F_f/d_f. \quad (7)$$

Here, t_p is the action time of the photodetonation regime and d_f is the threshold diameter of the absorption region at which the photodetonation regime is quenched.

By using these expressions, we estimated the parameters of a laser spark in experiment [7], where for the pulse energy $q = 280$ J and $t_r \sim 30$ μs, we have $\bar{W} \sim 10$ MW. By substituting this value into (5)–(7), we obtain for $P_0 = 0.1$ atm that $Z_p = 0.28$ cm, $t_r = 0.05$ μs, and $q = 0.5$ J and for $P_0 =$ 1 atm that $Z_p = 0.12$ cm, $t_r = 0.028$ μs, and $q = 0.238$ J. It follows from these data that for $\bar{W} \sim 10$ MW the photodetonation regime cannot provide the efficient absorption of laser pulses. At low intensities, the regime of a subsonic radiation wave also does not exist. In this case, the mechanism of a slow combustion wave, whose propagation velocity is too small (a few tens of metres per second), also probably does not act. It is possible that radiation was absorbed due to the successive action of optical breakdown in the focus, a photodetonation wave, a subsonic radiation wave, and bremsstrahlung absorption in the expanding plasma for ~ 15 μs.

Let us find the optimal values of W and t_r for the absorbed energy q. The corresponding expressions are obtained from (5)–(7):

For $P_0 = 1$ atm For $P_0 = 0.1$ atm

$$W = 21.7(qd_f/F_f)^{0.617}, \qquad W = 15(qd_f/F_f)^{0.588}, \quad (8)$$

$$t_r = 0.0455(qF_f/d_f)^{0.381}, \qquad t_r = 0.0665q^{0.411}(F_f/d_f)^{0.588}, \quad (9)$$

$$Z_p = 0.194q^{0.352}(F_f/d_f)^{0.648}. \; Z_p = 0.357q^{0.365}(F_f/d_f)^{0.635}. \quad (10)$$

The numerical values of these parameters for $d_f/F_f = 1$ and different values of P_0 and q are presented in Table 1.

Table 1.

q/J	$P_0 = 0.1$ atm			$P_0 = 1$ atm		
	W/MW	Z_p/cm	t_r/μs	W/MW	Z_p/cm	t_r/μs
10	58.1	0.83	0.17	90	0.44	0.11
100	225	1.97	0.439	372	0.98	0.263
1000	873	4.52	1.13	1540	2.21	0.63
280 [7]	411	2.86	0.665	702	1.41	0.39

Thus, of most interest for LJEs are pulses of duration ~ 0.2 μs. The laser pulse energy is limited by the condition of radiation transport without losses: $q = \pi D_r^2 q_b/4 \approx 15 - 40$ kJ. It is assumed here, based on the condition of a weak divergence of radiation at a long path from a radiation source to a reflector, that the beam diameter is $D_r = 100$ cm [1] and $q_b \approx 2 - 5$ J cm^{-2} is the threshold energy density (the laser wavelength is 10.6 μm) above which emission is observed in the atmosphere and acoustic effects appear, which are caused by the heating of aerosols [14]. The optical breakdown threshold in a gas on aerosols is 10–50 J cm^{-2} depending on their concentration and size (in wide-aperture beams). Therefore, the conditions of energy transport and absorption in sparks allow the use of repetitively pulsed laser radiation with the average power $\bar{W} \approx 20$ MW, in particular, short laser pulses with a high pulse repetition rate.

The maximum laser pulse energy is limited by the condition of obtaining a high efficiency of the use of laser radiation for producing the thrust. The momentum carried by a shock wave in a free gas is nonzero only at small distances from the explosion centre [14]. The specific momentum for a parabolic reflector is maximal ($J_1 \sim$ 550 N s J^{-1}) at the distance R_1, for which $R_1/R_d \sim 0.1$, where $R_d = 2.15(q/P_0)^{1/3}$ is the dynamic radius (the dimensional units cm, J, and atm are used). As the ratio R_1/R_d is increased from ~ 0.1 to 0.33, the value of J_1 decreases from ~ 550 down to 200 N s J^{-1}.

The possibility of using small values of R_1/R_d in LJEs is limited by the formation of a long-lived plasma with the characteristic radius comparable with the reflector size. At the late stages of thermal expansion of a spark, a cavern is formed with the low density ($\rho \ll \rho_0$) and high temperature (~ 8000 K) of the ionised gas. The movement of the contact boundary of a hot region ceases when pressures in the cavern and surrounding gas are equalised. In the spherical spark approximation, the cavern radius R_{cav} during the equalisation of pressures can be obtained from the expressions

$$\frac{R_{cav}}{R_d} = \frac{0.49 r_0^{0.29}}{(q/P_0)^{0.097}}, \tag{11}$$

$$\frac{t_{cav}}{t_d} \approx 0.374. \tag{12}$$

Here, r_0 [cm] is the initial radius of the spark; $t_d = R_d/C_0$ is the dynamic time; and C_0 is the sound speed. By setting $r_0 \approx Z_p/2$, we obtain from (11) the estimate for the cavern radius for the entire pressure range $P_0 = 0.1 - 1$ atm:

$$R_{cav}/R_d \approx 0.25(F_f/d_f)^{0.19} \approx 0.15 - 0.25. \tag{13}$$

One can see from (13) that the ratio R_{cav}/R_d is independent of the gas energy and pressure, its value being in the range of values of R_1/R_d where the maximum specific recoil momentum produced by the shock wave is achieved. For a hemispherical reflector, the maximum of the specific momentum J_1 is achieved for $R_1/R_d \approx 1$, its value, however, being small ($J_1 < 250$ N s J^{-1}). In this case, the plasma size is smaller than the reflector size.

Let us present the cavern radius and its formation time for the laser energy $q = 10^5$ J and pressures $P_0 = 1$ and 0.05 atm. The average power of the laser is $\bar{W} = 2 \times 10^7$ W and the pulse repetition rate is $f = 100$ Hz. We consider the start stage of a spacecraft and the end of its acceleration stage in the LJE regime (for higher parameters of the laser, the ablation regime begins). For $P_0 = 1$ atm, we have $R_{cav} = 15 - 25$ cm and $t_{cav} = 1.1$ ms, and for $P_0 = 0.1$ atm – $R_{cav} = 32 - 54$ cm and $t_{cav} = 2.36$ ms. If $t > t_{cav}$, the laser plasma is cooled due to its turbulent mixing with a cold surrounding gas. The characteristic time of this process is more than an order of magnitude exceeds t_{cav} from [15–17].

We considered here a spherical spark. However, real sparks in LJEs have the conical shape with a large cone angle, which makes the situation even worse. Under certain conditions at the late stage of the spark expansion, a cumulative jet can be formed [18, 19] in which a gas moves to the cone base (in our case, to the reflector). The plasma shape is no longer simply connected and resembles a torus.

Thus, in the case of the maximum radiation pulse, the plasma contacts the reflector surface, which can result in the damage of the reflecting layer. To reduce the gas-replacement time in the reflector, we proposed to use an air jet; however, this cannot solve the problem of the negative action of a large plasma sphere on the environment.

3. Mechanism of the resonance merging of shock waves in a LJE

The resonance merging of individual shock waves into a low-frequency quasi-stationary wave occurs generally as follows. Shock waves with the initial velocity greater than the sound speed C_0 are produced successively in a continuous medium. The propagation velocity V_0 of the pulsation region is lower than C_0. Shock waves merge to produce a quasi-stationary wave if the parameters of pulsation and medium satisfy certain criteria. Depending on the spatiotemporal structure of pulsations, this merging is characterised by a number of properties, of which the main is a long length of the high-pressure region. The wave-merging mechanism imposes no restrictions on the type of a medium, a source of pulsations and its energy. Depending on the structure of pulsations, the quasi-stationary wave may have different shapes.

We will show that the merging of the waves into a quasi-stationary wave solves the above-considered problems of radiation screening and thermal action of the laser plasma in a LJE. In addition, the quasi-stationary wave allows one to increase considerably the efficiency of using laser radiation due to an increase in the specific thrust (per unit power). Let us estimate the laser pulse energy and pulse repetition rate required for solving this problem. We will consider two methods based on the use of a spherical and 'plane' OPD. In both cases, a plane quasi-stationary wave is formed by using both the OPD and reflector geometry and also by a proper coupling of the laser radiation energy.

Thus, the merging of shock waves into a quasi-stationary wave provides the reduction of the laser pulse energy, thereby solving the problem of a large size R_{cav} of the plasma, because for the pulse energy ~ 1000 J and a high pulse repetition rate, the transverse dimensions of plasma (caverns) of the OPD are small compared to the reflector diameter; the plasma itself is carried out from the reflector by a jet injected to the central part of the reflector. In addition, the quasi-stationary wave and the engine geometry used allow the introduction of the laser radiation energy into a gas away from the reflector surface, which removes the problem of screening and thermal action; also, the specific thrust (recalculated to the average radiation power unit) increases.

4. Spherical OPD

In the general case a reflector has the shape a cylinder of length L_r, whose end is a receiver of repetitively pulsed laser radiation focused on the cylinder axis. The radiation intensity in the focus exceeds the optical breakdown threshold q_b in the atmospheric air. The value of q_b depends on the size and concentration of aerosol particles in the atmosphere and is 20–50 J cm^{-2} [13] for 1-μs pulses. A gas jet injected through the reflector end has a high velocity and is used for carrying out the OPD plasma (the radius of caverns does not exceed the jet radius) and providing the efficient conversion of laser radiation to shock waves. The jet can be formed with the help of an air collector. The cylinder walls transform the radial component of the momentum of spherical shock waves to the longitudinal component.

On the reflector input the trains of laser pulses producing an OPD are incident. The train repetition rate F depends on the gas-replacement time in the reflector. The pulses in a train have a high (tens of kilohertz) repetition rate f at which individual shock waves merge to produce an extended region of elevated pressure – a quasi-stationary wave. Such a wave in a free gas would have a spherical shape and pressure in it would rapidly decrease as its leading edge moves away from the OPD. In the limited space and for a certain relation between the reflector size and the OPD power, pressure appears which acts constantly for a time that is no shorter than the laser pulse train duration. The negative excess pressure on the receiving reflector and the force produced by it, which decelerates a spacecraft, can appear only after switching off radiation during the replacement of the heated gas by the atmospheric air. Unlike the case of a spherical or cylindrical explosion, the negative momentum of the unloading phase of a plane shock wave is small [14].

Let us estimate the parameters of a LJE of the required power for the acceleration scheme of a spacecraft described above. We assume that the pulse energy q is given. It is necessary to determine the optimal parameters of the reflector, jet, pulse repetition rate in trains, and train repetition rate. We assume that the average laser radiation power required for placing light spacecrafts in orbit is $\bar{W} \approx 10-20$ MW.

We will also take into account that, to avoid a decrease in the average power of a gas-dynamic laser, laser radiation should be modulated at a frequency of no less than 20 kHz. This imposes the restriction $q < 10^3$ J on the laser pulse energy. To avoid optical breakdowns in the path and on the reflector, the characteristic radius R_r of the reflector should be $30-50$ cm.

Earlier [1–3], we found the conditions under which a pulsed source of shock waves (for example, an OPD) produces the extended region of elevated pressure – a quasi-stationary wave. The length of this wave considerably exceeds the length of compression phases of shock waves from which it is formed. The source of waves can be immobile or can move at a subsonic speed. An OPD in a LJE is immobile and burns in the focus of laser radiation. In the absence of walls, such a discharge can produce a spherically symmetric quasi-stationary wave. Due to reflection of the latter from the walls, the radial component of its momentum is partially transformed to the longitudinal component. An excess pressure is established over the entire volume of the cylinder. The geometry of the problem becomes close to the case of a one-dimensional plane explosion at which the recoil momentum is maximal. The reflecting part of the reflector, which also serves as a receiver of the recoil momentum, is subjected to a force which weakly changes during the action of the laser pulse train.

The OPD produces a quasi-stationary wave when the conditions of stable generation of shock waves and the merging of their train are fulfilled. In the general case these conditions are

$$2.5M_0 > f^0 > 5.88(1 - M_0)^{1.5}, \tag{14}$$

where $M_0 = V_0/C_0$ is the dimensionless velocity of the OPD propagation in a free gas along some line and $f^0 = ft_d$ is the dimensionless pulse repetition rate. The left-hand side of (14), which restricts the region of stable generation of shock waves, can be written in the form

$$f_p = \frac{V_J}{2R_{cav}} = \frac{2.5V_J}{R_d}\left(\frac{P_J}{P_0}\right)^{1/3}. \tag{15}$$

Here, P_0 is the air pressure in the reflector at the beginning of the action of the laser pulse train; and P_J and V_J are the static pressure and velocity of a gas in the jet where the OPD is burning. If the laser pulse repetition rate is equal to the limiting frequency f_p of generation of shock waves or lower, the laser plasma is carried out from the focal region during the period between pulses. Each spark is produced in a fresh gas, and the OPD transforms $\sim 30\,\%$ of the laser radiation energy to periodic shock waves.

The OPD burns in the jet, and the shock waves generated by the OPD merge into a quasi-stationary wave in the surrounding air, which can be considered immobile with respect to the OPD. Therefore, $M_0 = 0$ in the right-hand side of (14), and the condition of shock-wave merging can be written in the form

$$f_q = 5.88C_0/R_d, \tag{16}$$

where f_q is the OPD frequency at which the quasi-stationary wave is established. Thus, the conditions of the efficient conversion of laser radiation to shock waves and their merging to quasi-stationary waves can be written in the form

$$f_q < f < f_p. \tag{17}$$

Here, the laser pulse repetition rate is

$$f = \bar{W}/q. \tag{18}$$

Figure 2 shows dependences (15), (16), and (18) for $\bar{W} = 20$ MW. According to (17), the working range of the q and f values is limited by a part in curve (18) between the intersection points with curves f_p and f_q. The values of f_p and f_q depend on the laser pulse energy, gas pressure in the reflector and jet, and the jet velocity V_J; note that the gas pressure and jet velocity can change during the acceleration of a spacecraft. This ambiguity in the choice of radiation parameters can be eliminated in the following way. Let us assume that the air pressure at the start of the spacecraft is $P_0 = P_{01}$. As the height and velocity of the flight increase, the values of P_0 and P_J decrease, and $P_0 = P_{02}$ at the end of the LJE action. Below, we assume for definiteness that

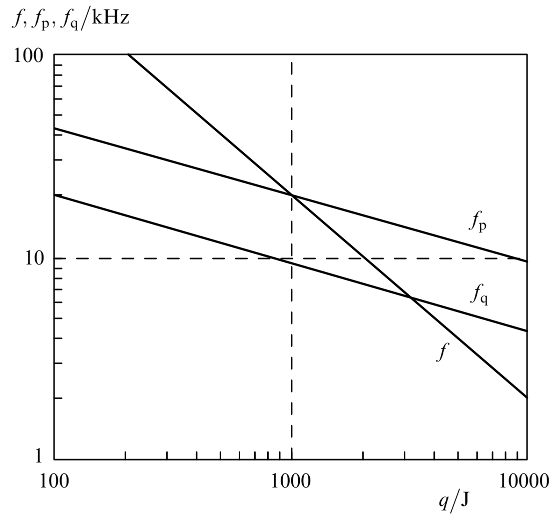

Figure 2. Conditions of the merging of shock waves into a quasi-stationary wave for the average OPD power $\bar{W} = 20$ MW, laser pulse repetition rate $f = \bar{W}/q = 20$ kHz and gas pressure $P_0 = 0.1$ atm.

$P_0 = 1$ atm and $P_{02} = 0.1$ atm. Because $f_p \sim P_J$ and $f_q \sim P_0$, curves f_p and f_q in Fig. 2 are displaced downwards with increasing height. We will consider the part of the curve f between its intersection points with the curve f_q for $P_{01} = 1$ atm and curve f_p for $P_{02} = 0.1$ atm as the working range of q and f. In this case, the boundary values of q and f are

$$q_{max} = \frac{2.2\times 10^8}{P_{01}^{1/2}}\left(\frac{\bar{W}}{C_0}\right)^{3/2} = 35\bar{W}^{3/2},$$
$$f_{min} = 4.52\times 10^{-3} C_0^{3/2}\left(\frac{P_{01}}{\bar{W}}\right)^{1/2} = \frac{28.3\times 10^3}{\bar{W}^{1/2}}, \tag{19}$$

$$q_{min} = \frac{8\times 10^8}{P_{J2}^{1/2}}\left(\frac{\bar{W}}{V_{J2}}\right)^{3/2},$$
$$f_{max} = 1.25\times 10{-}3V_{J2}^{3/2}\left(\frac{P_{J2}}{\bar{W}}\right)^{1/2}. \tag{20}$$

The average power $\bar{W}$ in (19) and (20) is expressed in megawatts. Let us take into account the restriction $f \approx$ 20 kHz imposed on the minimal pulse repetition rate in a gas-dynamic laser. By replacing f_{max} by f, we find the gas jet velocity at the final acceleration stage of the spacecraft:

$$V_{J2} = 86 f^{2/3}\left(\frac{\bar{W}}{P_{J2}}\right)^{1/3}; \tag{21}$$

the corresponding limiting frequency is

$$f_p = 100 f^{2/3}\left(\frac{\bar{W}}{q}\right)^{1/3}. \tag{22}$$

The pulse repetition rate and energy can have arbitrary values between their minimum and maximum values. The jet velocity V_J can be always selected so that the OPD plasma will be carried out from the focal region during the period between pulses. However, as q increases, the diameter of the gas jet and plasma trace also increases, resulting in the screening of radiation on the path to the reflector, or it is necessary to make an unacceptably large diameter of the reflector. The velocity V_J can be found from (21) by replacing P_{J2} by P_J, which depends on the current value of P_0. By assuming for the estimate that $\bar{W} = 20$ MW and $f = 2\times 10^4$ Hz, we obtain for $P_J = 1$ and 0.1 atm that $V_J = 1.73\times 10^5$ and 3.7×10^5 cm s^{-1}, respectively. Here, V_J is the jet velocity in the combustion zone of the OPD located at the distance $R_1 \sim (1-2)R_d$ from the nozzle from which the jet is issued. Therefore, the total pressure in the jet should considerably exceed the pressure in the reflector. The velocity V_J is related to the quasi-stationary pressure P_{br} upon deceleration of the gas flow by the expression

$$V_J = \frac{2C_J}{\gamma - 1}\left[\left(\frac{P_{br}}{P_J}\right)^{(\gamma-1)/\gamma} - 1\right]^{1/2}. \tag{23}$$

By assuming that $P_{br} \sim 2P_r \sim 4P_0$, $P_J = P_0$, the speed velocity in the jet is $C_J \approx 3.4\times 10^4$ cm s^{-1} and the adiabatic parameter is $\gamma = 1.4$, we obtain $V_J = 1.19\times 10^5$ cm s^{-1} (P_r is the gas pressure after OPD switching on). This value is lower than that required for maintaining the stable generation of shock waves.

The jet radius R_J should satisfy two opposite requirements: on the one hand, it should be sufficiently large compared to R_{cav} to provide the removal of the OPD plasma from the reflector, and on the other, the condition $R_J \ll R_{cav}$ should be fulfilled, because otherwise a great part of the energy of shock waves will be carried out by the supersonic jet and will not enter to the surrounding gas. The latter follows both from the geometric factor and the condition that the shock wave should have the intensity providing its propagation through the jet-immobile gas interface without losses. These conditions can be satisfied simultaneously when the cavern and jet radii are related by the expression

$$R_J = 0.3R_{cav} = 0.05R_{dJ} = 0.11(q/P_J)^{1/3}\ [\text{cm}], \tag{24}$$

where R_{dJ} is the dynamic radius of the jet.

In this case, optical breakdowns occur in the jet and a plasma being formed expands outside the jet. In the case of a high longitudinal component of the velocity, the plasma located outside the region of radius R_J also will be carried out from the reflector. Upon acceleration of the spacecraft, pressures P_0 and P_J decrease. In the pressure range $P_J = 1-0.1$ atm for a fixed value of q, the value of R_J should approximately increase twice. Otherwise the high-velocity jet will carry out not only the OPD plasma but also the shock waves generated by it. To avoid this, either the parameters of the jet and radiation should be changed according to (24) or all the parameters should be fixed, by maintaining P_J at the level of 1 atm (by using an appropriate air collector).

In experiments [11, 20], the OPD burned in a jet flowing out to immobile air. The radii of caverns and the plasma jet were ~ 2 mm, while the gas jet radius was varied from 1.5 to 3 mm. In these experiments, which were performed at velocities $V_J < 500$ m s^{-1}, no effect of R_J on the generation of shock waves was observed. Note, however, that sparks had the shape of a cone with the length exceeding the diameter of its base approximately by a factor of five.

The jet structure strongly changes under the action of the OPD. Two limiting cases can be considered. If $f \ll f_p$, the trace consists of the isolated regions of the decaying laser plasma. For $f \approx f_p$, the OPD forms a continuous plasma jet with the limiting velocity (with respect to the reflector) $V_p \approx V_J + C_p$ [21–23]. For a high energy density absorbed in a spark, the sound speed in the plasma is $C_p \approx (2-3)\times 10^5$ cm s^{-1}. Note also that away from the OPD (at a distance of ~ 2 m), the jet radius can increase up to $\sim 2R_{cav}$. This is caused by its slowing down and turbulent cooling acting after the end of adiabatic expansion (for $t > t_q$). At this stage, the gas temperature decreases from ~ 8000 K to the ambient temperature and the density is restored.

Based on the transverse size of the jet, radiation power losses in the laser plasma can be determined:

$$\delta\bar{W} = \frac{R_{caw}^2}{R_r^2} = \frac{0.04R_{dJ}^2}{R_r^2} = \frac{0.185(q/P_J)^{2/3}}{R_r^2}. \tag{25}$$

Let us find the reflector radius, by assuming that some level of losses, for example, δW is the limiting admissible level:

$$R_r = \frac{0.2R_{dJ}}{\delta W^{1/2}} = \frac{0.43(q/P_{J2})^{1/3}}{\delta W^{1/2}}. \tag{26}$$

For $\delta W \approx 0.03$, $P_J = 0.1$ atm, and $q = 1000$ J, the reflector radius is $R_r = 53$ cm. It is obvious that for $P_J \sim 1$ atm, R_r will be approximately half this value; however, its value should be the same as at the end of the acceleration stage of the spacecraft. Note that the value $R_r \sim 50$ cm also satisfies the conditions of radiation transport.

Let us determine the accelerating force produced by the OPD on the reflector shown in Fig. 1a. The principal difference of our approach from the known LJE schemes with a low optical breakdown repetition rate is that the OPD produces a quasi-stationary wave occupying the entire volume of a cylinder. Thus, we are dealing with a plane geometry of the problem in which the specific recoil momentum is maximal, whereas the negative excess pressure is minimal. The excess pressure $\delta P = P - P_0$ on the cylinder end, the force F_a acting on the end, and the specific thrust $F_a/\bar{W}$ are

$$\delta P = P_0 (R_d/R_{sp})^{1.64} \text{ [atm]}, \tag{27}$$

$$F_a = \pi R_r^2 \delta P, \tag{28}$$

$$F_a/\bar{W} = \pi R_r^2 \delta P/(q\bar{W}), \tag{29}$$

where R_{sp} is the distance between the OPD and cylinder walls, which is approximately equal to the focal distance of the reflector. Let us assume that $R_{sp} = a_r R_r$, where $a_r = 0.5 - 1$. Note that the ratio of the reflector radius to the dynamic radius for $P_0 = P_{01} = 1$ atm is close to unity:

$$\frac{R_1}{R_{d1}} = \frac{0.2}{\delta W^{1/2}} \left(\frac{P_{01}}{P_{J2}}\right)^{1/3}. \tag{30}$$

For $P_0 = P_{01} = 1$ atm, we obtain the ratios $R_r/R_{d1} = 1.15$ and 2.47 for two different pressures of the jet $P_{J2} = 1$ and 0.1 atm. This means that, if $R_1 \approx R_r$, the pressure on the reflector end can be considered uniformly distributed and described by expression (27). This is all the more true because a shock weave reflected from the cylinder side will act on the periphery of the reflector. The excess pressure is constant or grows during the pulse train:

$$\delta P = 14 P_0^{0.45} P_{J2}^{0.55} \frac{(\delta W)^{0.82}}{a^{1.64}} \text{ [atm]}. \tag{31}$$

The force acting on the reflector is

$$F_a[\text{N}] = 10\pi R_r^2 P_0 \left(\frac{R_d}{aR_r}\right)^{1.64} = 10\pi R_r^{0.36} P_0 \left(\frac{R_d}{a}\right)^{1.64}. \tag{32}$$

The specific force (per 1 MW of the average power) is

$$J[\text{N MW}^{-1}] = \frac{F_a}{\bar{W}} = \frac{192 \times 10^6 P_0^{0.45}}{a^{1.64} f q^{1/3}}. \tag{33}$$

In the simplest LJE scheme (Fig. 1a), a spacecraft is accelerated under the action of laser pulse trains following with the repetition rate F. The repetition rate of laser pulses in trains is $f \gg F$. Each laser pulse train produces the OPD, which in turn generates a train of shock waves merging into a quasi-stationary wave. The air in the reflector heats up considerably within a time τ_t and its density becomes low. As a result, a further input of laser radiation can be inefficient. After switching off radiation, the gas in the reflector is replaced by the cold atmospheric air. The duration of this process is $\tau_p \sim a_p L_r/C_0$. Here, $a_p \approx 1 - 2$ is a coefficient depending on the geometry of the reflector and spacecraft, and the velocity of the latter. The minimal duration τ_t of the train is equal to the time for which a shock wave produced by the first spark of the train propagates the distance from the OPD to the reflector and back:

$$\tau_t = \frac{2R_1}{C_0} = \frac{2R_r}{C_0} = \frac{0.86}{C_0 \delta^{1/2}} \left(\frac{q}{P_{J2}}\right)^{1/3} = 4.63 \times 10^{-4} q^{1/3}. \tag{34}$$

Hereafter, it is assumed in final expressions that the admissible screening level of radiation is $\delta = 0.03$, the pressure in the jet at the end of the shock-wave amplification regime is $P_{J2} = 0.1$ atm, and $a_p = 1$. The ratio of characteristic times $\tau_p/\tau_t = 0.5 a_p L_p/R_1$ achieves the minimal value $0.5a_p$ when the OPD burns on the cut of the open end of the cylinder. The average value of the accelerating force is

$$\bar{F}_a = F_a \frac{1}{1 + \tau_p/\tau_t} = \frac{2}{3} F_a. \tag{35}$$

The train repetition rate F, their energy q_t, and average power $\bar{W}$ are

$$F = \frac{3.95 \times 10^4 \delta^{1/2}}{1 + 0.5a_p} \left(\frac{P_{J2}}{q}\right)^{1/3} \approx \frac{2090}{q^{1/3}}, \tag{36}$$

$$q_t = \bar{W}\tau_t = \frac{0.86\bar{W}}{C_0 \delta^{1/2}} \left(\frac{q}{P_{J2}}\right)^{1/3} = 4.63 \times 10^{-4} \bar{W} q^{1/3}, \tag{37}$$

$$\bar{W} = q_t F = \frac{\bar{W}}{1 + \tau_p/\tau_t} = \frac{\bar{W}}{1 + 0.5a_p} = \frac{2}{3}\bar{W}. \tag{38}$$

Note that these relations were obtained for the lower bound of the minimal duration of the train. The results of preliminary calculations show this value can be increased by several times due to the properties of the quasi-stationary wave and geometry of the reflector – receiver of the recoil momentum.

5. LJE parameters in the monoreflector scheme

Let us determine the LJE parameters by using the model considered above. We assume that the average power of laser pulse trains is 20 MW, the air pressure at the start of a spacecraft is $P_0 = P_{01} = 1$ atm, and $P_0 = P_{02} = 1$ atm at the end of the LJE operation. In addition, we assume that the static pressure in the jet is equal to the surrounding air pressure ($P_J = P_0$).

The obvious advantages of the scheme considered above compared to traditional methods are a higher efficiency of utilising laser radiation and the absence of the laser-plasma contact with the optical surface of the reflector and the absence of laser radiation screening. In addition, this scheme is technologically simple. For $\bar{W} \approx 20$ MW, the following laser parameters are optimal: the pulse energy $q = 1$ kJ, the pulse repetition rate $f = 20$ kHz, the duration of laser pulse trains $\tau_t = 5$ ms, and the train repetition rate $F = 200$ Hz. However, gas-dynamic lasers can efficiently generate pulses with a pulse repetition rate of $f > 50$ kHz [9]. In this case, the velocity of a gas jet injected to the reflector proves to be too high for technical realisation in model experiments on a stand.

6. Array reflector

The scheme of an array reflector is shown in Fig. 1b. All parameters (with the subscript m) in the expressions presented below refer to one reflector of the array; then, summation over the number N of elements is performed $[R_{\mathrm{cav}}/R_{\mathrm{d}} \approx 0.25(F_{\mathrm{f}}/d_{\mathrm{f}})^{0.19} \approx (0.15-0.25)R_{\mathrm{cav}\,m} = R_{\mathrm{cav}}/N^{1/3}]$:

$$f_{\mathrm{p}m} = \frac{V_{\mathrm{J}m}}{2R_{\mathrm{cav}m}} = \frac{2.5V_{\mathrm{J}m}}{R_{\mathrm{d}m}}\left(\frac{P_{\mathrm{J}m}}{P_0}\right)^{1/3} = f_{\mathrm{p}}N^{1/3}, \tag{39}$$

$$f_{\mathrm{q}m} = 5.88C_0/R_{\mathrm{d}m} = f_{\mathrm{q}}N^{1/3}, \tag{40}$$

$$f_{\mathrm{q}} < f < f_{\mathrm{p}}. \tag{41}$$

Here, the laser pulse repetition rate is

$$f_m = \bar{W}_m/q_m = f, \tag{42}$$

$$q_{\max m} = \frac{2.2\times10^8}{P_{01}^{1/2}}\left(\frac{\bar{W}_m}{C_0}\right)^{3/2} = \frac{q_{\max}}{N^{3/2}},$$
$$q_{\min m} = \frac{8\times108}{P_{\mathrm{J}2m}^{1/2}}\left(\frac{\bar{W}_m}{V_{\mathrm{J}2m}}\right)^{3/2} = \frac{q_{\min}}{N^{3/2}}, \tag{43}$$

$$f_{\mathrm{w}\max m} = 1.25\times10^{-3}V_{\mathrm{J}2m}^{3/2}\left(\frac{P_{\mathrm{J}2m}}{\bar{W}_m}\right)^{1/2} = N^{1/2}f_{\mathrm{w}\max}. \tag{44}$$

In these expressions and below, the average power is given in megawatts. Let us take into account the restriction $f \approx 20$ kHz on the minimal pulse repetition rate in a gas-dynamic laser. By equating this value of f to $f_{\mathrm{w}\max}$, we find the velocity of the gas jet at the final acceleration stage of the spacecraft:

$$V_{\mathrm{J}2m} = 86f^{2/3}\left(\frac{\bar{W}_m}{P_{\mathrm{J}2m}}\right)^{1/3} = \frac{V_{\mathrm{J}2}}{N^{1/3}}. \tag{45}$$

By substituting $V_{\mathrm{J}2}$ into (39), we obtain

$$f_{\mathrm{p}m} = 100f^{2/3}\left(\frac{\bar{W}_m}{q_m}\right)^{1/3} = f_{\mathrm{p}}. \tag{46}$$

Here, f is the fixed value of the laser pulse repetition rate and q is the argument of the function f_{p} shown in Fig. 2. The jet velocity is

$$V_{\mathrm{J}} = \frac{2C_{\mathrm{J}}}{\gamma-1}\left[\left(\frac{P_{\mathrm{br}m}}{P_{\mathrm{J}m}}\right)^{(\gamma-1)/\gamma} - 1\right]^{1/2}, \tag{47}$$

$$R_{\mathrm{J}m} = 0.3R_{\mathrm{cav}m} = 0.05R_{\mathrm{dJ}m}$$
$$= 0.11(q_m/P_{\mathrm{J}m})^{1/3}\ [\mathrm{cm}] = R_{\mathrm{J}}/N^{1/3}. \tag{48}$$

The losses of the average radiation power in the laser plasma in the mth element of the reflector are

$$\bar{\delta}_m = \frac{R_{\mathrm{cav}m}^2}{R_{\mathrm{r}m}^2} = \frac{0.04R_{\mathrm{dJ}m}^2}{R_{\mathrm{r}m}^2} = \frac{0.185(q_m/P_{\mathrm{J}m})^{2/3}}{R_{\mathrm{r}m}^2}. \tag{49}$$

Let us determine the reflector radius assuming that the level of losses $\delta W = 0.03$ is the limiting admissible level:

$$R_{\mathrm{r}m} = \frac{0.2R_{\mathrm{dJ}m}}{\delta_m^{1/2}} = \frac{0.43(q_m/P_{\mathrm{J}2m})^{1/3}}{\delta_m^{1/2}} = \frac{R_{\mathrm{r}}}{N^{1/3}}, \tag{50}$$

where δ_m are radiation losses in the laser plasma per element of the array reflector. For a square array reflector, half the square side is

$$R_M = R_{\mathrm{r}m}N^{1/2} = R_{\mathrm{r}}N^{1/6}.$$

The excess pressure producing the accelerating thrust is

$$\delta P = P_0(R_{\mathrm{d}}/R_1)^{1.64}\ [\mathrm{atm}], \tag{51}$$

$$F_{\mathrm{a}} = \pi R_{\mathrm{r}}^2\delta P,$$
$$\frac{F_{\mathrm{a}}}{\bar{W}} = \frac{\pi R_{\mathrm{r}}^2\delta P}{W}, \tag{52}$$

$$\frac{R_{\mathrm{r}m}}{R_{\mathrm{d}1m}} = \frac{0.2}{\delta^{1/2}}\left(\frac{P_{01m}}{P_{\mathrm{J}2m}}\right)^{1/3} = \frac{R_{\mathrm{r}}}{R_{\mathrm{d}1}}, \tag{53}$$

$$\delta P_m = 14P_{0m}^{0.45}P_{\mathrm{J}2m}^{0.55}\frac{\delta^{0.82}}{a^{1.64}}\ [\mathrm{atm}], \tag{54}$$

where $a = (R_{\mathrm{d}}/R_{\mathrm{d}1})^{1.64}$.

Let us determine the average values of parameters for periodic laser pulse trains (with the subscript t). The train duration is

$$\tau_{\mathrm{t}m} = \frac{2R_{1m}}{C_0} = \frac{2R_{\mathrm{r}m}}{C_0} = \frac{0.86}{C_0\delta_m^{1/2}}\left(\frac{q_m}{P_{\mathrm{J}2m}}\right)^{1/3}$$
$$= 4.63\times10^{-4}q_m^{1/3} = \frac{\tau_{\mathrm{t}}}{N^{1/3}}. \tag{55}$$

The average force acting on an element of the array reflector in periodic trains is

$$\bar{F}_{\mathrm{a}m} = F_{\mathrm{a}m}\frac{1}{1+\tau_{\mathrm{p}m}/\tau_{\mathrm{t}m}} = \frac{2}{3}F_{\mathrm{a}m} = \frac{2}{3}\frac{F_{\mathrm{a}}}{N^{2/3}}. \tag{56}$$

The force acting on the entire array reflector is

$$\bar{F}_{\mathrm{a}M} = N\bar{F}_{\mathrm{a}m} = \frac{2}{3}F_{\mathrm{a}}N^{1/3} = \bar{F}_{\mathrm{a}}N^{1/3}.$$

The train repetition rate is

$$F_m = F_M = \frac{3.95\times10^4\delta_m^{1/2}}{1+0.5a_{\mathrm{p}m}}\left(\frac{P_{\mathrm{J}2m}}{q_m}\right)^{1/3} \approx \frac{2090}{q_m^{1/3}} = N^{1/3}F. \tag{57}$$

The pulse train energy per element of the array reflector is

$$Q_{\mathrm{t}m} = \bar{W}_m\tau_{\mathrm{t}m} = \frac{0.86\bar{W}_m}{C_0\delta_m^{1/2}}\left(\frac{q_m}{P_{\mathrm{J}2m}}\right)^{1/3} =$$

$$= 4.63 \times 10^{-4} \bar{W}_m q_m^{1/3} = \frac{Q}{N^{4/3}}, \quad (58)$$

where Q is the train energy for a monoreflector.

The train energy in the array reflector consisting of N elements is

$$Q_{tM} = N\bar{W}_m \tau_{tm} = \frac{Q}{N^{1/3}}.$$

The average radiation power of periodic trains for the array reflector is

$$\bar{W}_{tM} = Q_{tM} F_M = \bar{W}_t = \frac{2}{3}\bar{W}. \quad (59)$$

The specific force acting on the array reflector is

$$J_M\,[\mathrm{N\ MW^{-1}}] \equiv \frac{F_{aM}}{\bar{W}_{tM}} = JN^{1/3}. \quad (60)$$

7. LJE based on the resonance merging of shock waves

7.1 Mechanism and scheme of acceleration

Laser pulses with a high repetition rate produce an OPD. Shock waves generated by the OPD merge to produce a high-pressure region – a quasi-stationary wave, thereby creating a permanent accelerating force. An air jet injected to the reflector provides a stable generation of shock waves and a removal of the laser plasma from the reflector. An array reflector allows one to use high-power laser pulses with a high repetition rate. Short 100–200-ns laser pulses are efficiently absorbed upon sharp focusing of radiation in the reflector. The cylindrical walls of a receiver of a mechanical momentum convert a part of the radial component of the momentum of the quasi-stationary wave to the longitudinal component acting on the reflector. This makes it possible to increase considerably pressure and, hence, the efficiency of utilising laser radiation.

7.2 Advantages of the method

(i) The specific thrust is $J = 1000 - 2500$ N MW^{-1}, which is several times higher than the level achieved earlier (200–500 N MW^{-1})

(ii) The method eliminates the problems inherent in traditional methods (see section 3) such as radiation screening by the laser plasma (in the case of low-energy laser pulses, the transverse size of the laser plasma is small), thermal action of the laser plasma on the reflector (the OPD is removed from the reflector surface), and shock loads (a constantly acting force is produced).

7.3 The LJE parameters (initial data)

(i) The average power of repetitively pulsed laser radiation is $\bar{W} = 20$ MW and the radius of the radiation receiver (reflector) is $R_r \sim 50$ cm.

(ii) Radiation receiver consists of $N = 1 - 10$ elements, each of them containing a reflector (served also as receiver of the mechanical momentum) and has cylindrical walls.

(iii) A gas-dynamic CO_2 laser emitting 10.6-μm pulses at a pulse repetition rate of 50–100 kHz is used. The lasing efficiency decreases at lower pulse repetition rates.

(iv) The air pressure at the start of the spacecraft is $P_0 = 1$ atm and at the end of the LJE operation – 0.1 atm (at height ~ 30 km).

7.3.1 Monoreflector

The reflector radius is selected from the condition of low radiation losses in the laser plasma ($\delta = 0.03$). The excess pressure is

$$\delta P = 14 P_0^{0.45} P_{J2}^{0.55} \frac{\delta^{0.82}}{a_r^{1.64}} = 0.68 P_0^{0.45}\ [\mathrm{atm}], \quad (61)$$

where $P_{J2} = 0.1$ atm is a pressure in the jet at the end of the LJE regime; $a_r = R_1/R_r = 0.5$; and R_1 is the distance from the OPD to the reflector. The force acting on the reflector is

$$F_a\ [\mathrm{N}] = 10\pi R_r^2 \delta P = \frac{201 q^{0.67} P_0^{0.45}}{a_r^{1.64}} = 626 q^{0.67} P_0^{0.45}. \quad (62)$$

The rate and radius of the gas jet are

$$V_J\,[\mathrm{m s^{-1}}] = 0.86 f^{2/3} \left(\frac{\bar{W}\,[\mathrm{MW}]}{P_J} \right)^{1/3}, \quad (63)$$

$$R_J = 0.11 (q/P_J)^{1/3}\ [\mathrm{cm}]. \quad (64)$$

We determine from (61)–(64) the LJE parameters for the pulse repetition rates $f = 2 \times 10^4$ and 10^5 Hz. Parameters at the start of the spacecraft ($P_0 = 1$ atm) are denoted by the subscript 1 and by 2 at the end of the LJE operation ($P_0 = 0.1$ atm).

Laser pulse repetition rate is $f = 2 \times 10^4$ Hz.

The pulse energy is $q = 1000$ J, the reflector radius is $R_r = 50$ cm, the distance from the OPD to the reflector is $R_1 = 25$ cm.

The forces acting on the reflector are $F_{a1} = 64 \times 10^3$ N and $F_{a2} = 23 \times 10^3$ N.

The specific forces (per 1 MW of average power) are $J_1 = 2600$ N MW^{-1} and $J_2 = 930$ N MW^{-1}.

The gas jet velocities are $V_{J1} = 1725$ m s^{-1} and $V_{J2} = 3716$ m s^{-1}.

The jet radii are $R_{J1} = 1$ cm and $R_{J2} = 2.4$ cm.

Laser pulse repetition rate is $f = 10^5$ Hz.

The pulse energy is $q = 200$ J, the reflector radius is $R_r = 31$ cm, the distance from the OPD to the reflector is $R_1 = 15$ cm.

The forces acting on the reflector are ($F_a = 21.8 P_0^{0.45}$ [N]) $F_{a1} = 21.8 \times 10^3$ N and $F_{a2} = 7.73 \times 10^3$ N.

The specific forces (per 1 MW of average power) are ($J = 906 P_0^{0.45}$) $J_1 = 906$ N MW^{-1} and $J_2 = 317$ N MW^{-1}.

By decreasing the distance R_1 down to 9.5 cm ($a_r = 0.3$), we can increase the force and the specific force. In this case, the parameters F_a and J increase by a factor of 2.3: $F_{a1} = 50.1 \times 10^3$ N, $F_{a2} = 17.78 \times 10^3$ N, $J_1 = 2084$ N MW^{-1} and $J_2 = 729$ N MW^{-1}.

The gas jet velocities are $V_{J1} = 5048$ m s^{-1} and $V_{J2} = 10880$ m s^{-1}.

The jet radii are $R_{J1} = 0.64$ cm and $R_{J2} = 1.4$ cm.

The production of such a jet in the LJE is complicated by the fact that even for the pulse repetition rate $f = 50$ kHz the jet velocity is too high: $V_{J1} = 3175$ m s^{-1} and $V_{J2} = 6840$ m s^{-1}.

Thus, an LJE with a monoreflector has good parameters and can be realised by using a laser pulse repetition rate of

~ 20 kHz. At higher pulse repetition rates, the LJE stabilisation is complicated by the necessity of using high-velocity (~ 5 km s^{-1}) gas jets. Another disadvantage of the monoreflector is that the control of the flight with the help of the laser engine is complicated.

7.3.2 Array reflector

The problems of the development of the LJE based on the merging of shock waves generated by laser pulses with a high (~ 100 kHz) repetition rate and of the control of the flight trajectory with the help of the LJE can be solved by using an array reflector consisting of N monoreflectors. The array is irradiated by laser pulses with the energy q and average power $\bar{W}$. We assume that the radii R_{rm} of the elements of the array reflector are the same and the elements are irradiated by laser pulses with the same parameters $q_m = q/N$ and $W_m = \bar{W}/N$. The array reflector produces the array of OPDs, which are stabilised by a jet with the velocity V_{Jm} and do not interact with each other.

The parameters with subscripts m and M in the expressions presented below correspond to the element and array, respectively; if these subscripts are absent, the notation refers to the monoreflector for the energy q and average power $\bar{W}$. The number of elements should provide the solution of the problem of a high-velocity jet. We assume that $N = 8$ (there is no point in using a greater value of N). The numerical values presented after expressions (65)–(70) were obtained for $\bar{W} = 20$ MW ($W_m = 2.5$ MW), $f = 10^5$ Hz, $q = 200$ J ($q_m = 40$ J), and $a_{rm} = 0.3$. As before, parameters at the start of the spacecraft ($P_0 = 1$ atm) are denoted by the subscript 1 and by the subscript 2 at the end of the LJE operation ($P_0 = 0.1$ atm).

The radius of the cylinder of an elementary reflector is

$$R_{rm} = \frac{0.2 R_{dJm}}{\delta_m^{1/2}} = \frac{0.43 (q_m / P_{J2m})^{1/3}}{\delta_m^{1/2}} = \frac{R_r}{N^{1/3}} = 15.5 \text{ cm}, \quad (65)$$

and the distance from the reflector to focus is ~ 5 cm.

The characteristic size of the array reflector is ~ 90 cm. The excess pressure is

$$\delta P_m = 14 P_{0m}^{0.45} P_{J2m}^{0.55} \frac{\delta^{0.82}}{a_m^{1.64}} = 1.56 P_0^{0.45} \text{ [atm]}, \quad (66)$$

therefore, $\delta P_{m1} = 1.56$ atm and $\delta P_{m2} = 0.55$ atm.

An element of the array reflector is subjected to the average force

$$F_{am} \text{ [N]} = \frac{81.4 q_m^{0.67} P_{0m}^{0.45}}{a_m^{1.64} P_{J2m}^{0.12} \delta_m^{0.18}} = \frac{F_a}{N^{0.67}} = \frac{F_a}{4}, \quad (67)$$

which gives $F_{am1} = 12.5 \times 10^3$ N and $F_{am2} = 4.45 \times 10^3$ N.

The array reflector is subjected to the average force

$$F_{aM} = N F_{am} = N^{1/3} F_a, \quad (68)$$

therefore, $F_{aM1} = 100 \times 10^3$ N and $F_{am2} = 35.6 \times 10^3$ N.

An element of the array reflector is subjected to the specific force (per 1 MW of average power)

$$J_m \text{ [N MW}^{-1}] = \frac{F_{am}}{\bar{W}_m}; \ \frac{81.4 \times 10^6 P_{0m}^{0.45}}{a_m^{1.64} f q_m^{1/3} P_{J2m}^{0.12} \delta_m^{0.18}}$$

$$= \frac{170 \times 10^6 P_{0m}^{0.45}}{a^{1.64} f q_m^{1/3}} = N^{1/3} J, \quad (69)$$

which gives $J_{m1} = 4170$ N MW^{-1} and $J_{m2} = 1460$ N MW^{-1}.

The specific force for the array reflector is the same as for one element:

$$J_M = F_{aM} / \bar{W} = N^{1/3} J.$$

The jet velocities in reflectors are

$$V_{J2m} = 86 f^{2/3} \left(\frac{\bar{W}_m}{P_{J2m}} \right)^{1/3} = \frac{V_{J2}}{N^{1/3}}, \quad (70)$$

and $V_{J1} = 2520$ m s^{-1} and $V_{J2} = 5440$ m s^{-1}.

Note in the conclusion of this section that

(i) the flight can be controlled by varying the thrust of a laser engine in the corresponding elements of the array reflector; and

(ii) the increase in the number of reflector elements is accompanied by the increase in the aerodynamic resistance in air collectors.

8. Conclusions

In this paper, we called attention to 'renaissance' in the field of laser jet propulsion supported in many countries. We confirmed that Russia still occupies a leading place in the development of laser systems and control of the laser radiation parameters, as well as in the investigation of new mechanisms of the LJE propulsion. The high efficiency of gas-dynamic lasers with a variable temporal structure of radiation for launching various nano- and microsatellites into space and maintaining them in orbit is pointed out.

Taking into account the advances of Russia in the development of high-power gas-dynamic lasers as the main element of the efficient LJE for launching small satellites, we proposed the Impulsar project, which is the logical continuation and development of pioneering papers of A.M. Prokhorov and F.B. Bunkin [24], for realisation in our country and development of the international collaboration in space with the aim to create the next generation of communication systems, in particular, for the development of the global super-high-speed Internet system.

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