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Formation of a narrow beam from an excimer laser pumped by gamma rays

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***Abstract*. A laser pumped by a travelling gamma-radiation wave and consisting of a cylindrical part forming spontaneous superradiation and a conical amplifier is considered. The energy parameters of an excimer conical KrF amplifier are investigated. The factors influencing the divergence of induced radiation at the output of the conical amplifier are analysed for various durations of a pump pulse. It is shown that the divergence of radiation emitted by the laser with an active medium length of 10 m may be as high as 10^{-4} rad. The scheme of laser-beam focusing on the target for the purposes of laser-induced fusion is considered.**

Keywords: *gamma-radiation pumping, radiation divergence, excimer active medium, spontaneous radiation.*

1. Introduction

The application of hard penetrating radiation (gamma rays and neutrons) for pumping provides unique possibility for creating powerful excimer lasers [1, 2]. The results of experimental investigations of the one-pass former of a narrow laser beam excited by gamma rays are reported in Ref. [1]. In Ref. [2], a conical XeF amplifier pumped by gamma rays is investigated theoretically and the obtained results are compared with the experimental results described in Ref. [1].

The problem of laser-induced fusion (LIF) requires, in addition to a high energy ($\sim 10^6$ J), a low divergence of radiation, which makes it possible to focuse it on a target of size ~ 1 mm. This paper is devoted to the formation of collimated radiation emitted by an excimer laser pumped by gamma rays and to focusing of laser radiation from several lasers on a target.

Low-divergence radiation is usually produced by means of optical cavities. For a pump pulse duration $t_\gamma \leqslant 2L/c$ (where L is the length of the active element and c is the velocity of light), the resonator method is inapplicable for producing low-divergence radiation in a large active volume of an excimer laser.

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Another widely used method for obtaining low-divergence radiation (down to the diffraction limit) involves the application of a system consisting of a master oscillator (MO) and an amplifier. Such a system usually employs a low-power MO forming low-divergence radiation with the help of a cavity and several amplifiers with increasing apertures. When the active media of amplifiers and MO are pumped by gamma rays, the MO radiation wave front lags behind the pump wave front. In this connection, MO with an autonomous pump source must be used in such systems.

Note that telescopes cannot be used in a laser system pumped by gamma rays for matching the apertures of the amplifying stages. When amplifying stages are arranged along the direction of propagation of gamma rays, the application of matching telescopes suppresses gamma radiation and leads to a delay of the stimulated radiation wave front from the pump wave front. Thus, the application of an amplifier with a continuously diverging aperture is of fundamental importance for a laser pumped by gamma rays.

In systems intended for LIF, it is inexpedient to use an autonomous MO in view of the difficulty of the synchronisation of its radiation with gamma rays exciting the amplifier. Synchronisation is simplified by increasing the duration of a radiation pulse from the autonomous MO, but in this case the main light pulse on the target is preceded by an MO radiation pulse, leading to a deterioration of the radiation contrast.

An analysis of the requirements to the systems for formation of low-divergence radiation and to devices for laser beam focusing on a target resulted in a basically new system proposed in our earlier publication [3], a conical former of a narrow laser beam.

A conical beam former consists of two elements optically coupled with one another through a small-diameter aperture d_0 (Fig. 1a). In the first element (so-called speed-up part), the radiation field synchronised with the gamma-radiation pump wave is formed and the required radiation intensity is

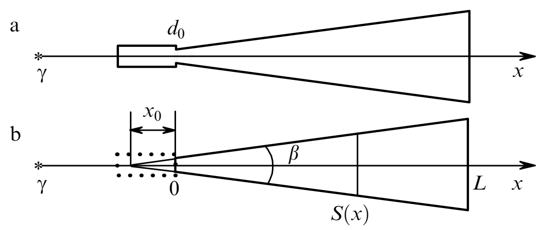

Figure 1. (a) Conical narrow beam former and (b) conical amplifier.

ensured. The axis of the second element (conical amplifier proper) coincides with the direction of propagation of gamma rays. Under certain conditions, the population inversion in the conical amplifier will be dumped only by radiation passing though the coupling aperture. The divergence of the laser beam in this case is $\theta \approx d_0/L$, where d_0 is the diameter of the coupling aperture and L is the length of the conical amplifier. The present study is devoted mainly to an analysis of the formation of low-divergence radiation in the proposed system.

2. Calculation of energy parameters of an excimer KrF amplifier with expanding beam geometry

Consider the active medium of a KrF laser. To estimate the parameters of the conical amplifier for a typical pump intensity $W_0 \approx 10-20$ MW cm^{-2} , we assume, in accordance with the results presented in Ref. [4], that the gain $g_0 = 0.18$ cm^{-1}, the absorption coefficient $\alpha_0 = 0.013$ cm^{-1}, and the saturation intensity $I_s = 10$ MW cm^{-2} (the maximum efficiency is $\sim 10\,\%$).

Consider the amplification of a light beam passing through a conical amplifier with the input aperture area $S_0 = S(0)$ and length L for the above parameters of the active medium (Fig. 1b). The radiation intensity distribution over the amplifier length with an expanding beam geometry can be written in the form [5]

$$\frac{d\Phi}{dx} = \frac{g_0\Phi}{1+\Phi} - \alpha_0\Phi - \frac{\Phi}{S}\frac{dS}{dx}, \quad (1)$$

where $\Phi = I/I_s$ is the radiation intensity normalised to the saturation intensity and $S(x)$ is the cross-sectional area of the active medium.

For a conical amplifier (Fig. 1b), $S(x) = S_0(1 + x/x_0)^2$, where $x_0 = d_0/[2\tan(\beta/2)]$ is the distance from the input aperture of the cone to its vertex and β is the cone angle. Taking this into account, we can write Eqn (1) in the form

$$\frac{d\Phi}{dx} = \frac{g_0\Phi}{1+\Phi} - \alpha_0\Phi - \frac{2\Phi}{x+x_0}. \quad (2)$$

The efficiency η of energy extraction in an amplifier of length L and volume V can be presented in the form [5]

$$\eta(L) = \frac{\psi(L)-\psi(0)}{\psi_{\max}}, \quad \psi(L) = \frac{\Phi(L)S(L)}{S(0)}, \quad (3)$$

where $\psi(L)$ and $\psi(0)$ are radiant fluxes at the output and input of the conical amplifier, respectively, and $\psi_{\max} = g_0 V/S_0$ is the maximum possible radiant flux emerging from the active volume of the amplifier in the absence of radiation absorption in it. As a result, we obtain the following expression for the efficiency of the conical amplifier:

$$\eta(L) = [\psi(L)-\psi(0)]\left[g_0\left(1+\frac{L}{x_0}+\frac{L^2}{3x_0^2}\right)L\right]^{-1},$$
$$\frac{d\psi}{dx} = g_0\psi\left[1+\psi\left(1+\frac{x}{x_0}\right)^{-2}\right]^{-1} - \alpha_0\psi. \quad (4)$$

In the particular case of a cylindrical amplifier ($x_0 = \infty$, $\psi = \Phi$), the solution of the differential equation (4) can be represented in the form of the transcendental equation

$$\psi(L) = \frac{g_0}{\alpha_0} - 1 - \left[\frac{g_0}{\alpha_0} - 1 - \psi(0)\right]$$
$$\times \exp\left\{\frac{\alpha_0}{g_0}\left[\ln\frac{\psi(L)}{\psi(0)} - (g_0-\alpha_0)L\right]\right\}. \quad (5)$$

where

$$\eta = \frac{\Phi(L)-\Phi(0)}{g_0 L}, \quad \frac{d\Phi}{dx} = \frac{g_0\Phi}{1+\Phi} - \alpha_0\Phi. \quad (6)$$

One can see from Eqn (6) that as the amplifier length increases, the radiation intensity saturates, so that $\Phi_{\max} = (g_0-\alpha_0)/\alpha_0$. It can also be easily derived from Eqn (6) that, for a layer Δx of the amplifier, there exists an optimal intensity $\Phi_{\rm opt}$ for which the efficiency of energy extraction is maximum ($\eta_{\max}$). The efficiency $\eta_{\max}$ can be determined from the condition

$$\frac{d\eta}{dx} = \frac{1}{g_0}\frac{d}{dx}\frac{d\Phi}{dx} = 0. \quad (7)$$

As a result, we obtain

$$\eta_{\max} = \left[1-\left(\frac{\alpha_0}{g_0}\right)^{1/2}\right]^2, \quad \Phi_{\rm opt} = \left(\frac{g_0}{\alpha_0}\right)^{1/2} - 1. \quad (8)$$

Equation (4) was solved numerically (by varying x_0) for different conical amplifiers. The radiation intensity at the amplifier input varied in the range $1 \leqslant \Phi(0) \leqslant \Phi_{\max}$ since only in this case one can expect a high stability of the amplifier to spontaneous emission noise. For the values of $g_0 = 0.18$ cm^{-1} and $\alpha_0 = 0.013$ cm^{-1} chosen by us for calculations, we obtain $\Phi_{\max} = 12.8$, $\Phi_{\rm opt} = 2.7$, and $\eta_{\max} = 0.53$.

The results of numerical calculations of the energy extracted from the conical amplifiers for the input signal intensity $\Phi(0) = 1$ are presented in Fig. 2. The case $x_0 = \infty$ corresponds to a cylindrical amplifier. For a cylindrical amplifier length of 10 m, the efficiency of energy extraction is $\eta = 0.066$, which is much lower than in conical amplifiers of the same length. The value of η for a conical amplifier increases with the cone angle β (which corresponds to values of x_0 smaller than in Fig. 2). For a conical amplifier with the

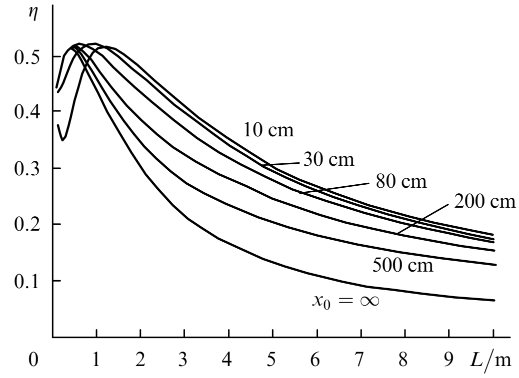

Figure 2. Efficiency η of energy extraction from a conical amplifier as a function of its length L for $\Phi(0) = 1$ and different values of x_0.

parameters $S_0 = 1$ cm^2, $x_0 = 10$ cm, and $L = 10$ m ($\beta = 6.5^\circ$), we have $\eta = 0.18$, which is almost three times larger than for a cylindrical amplifier of the same length. Therefore, the characteristic energy losses $1 - \eta/\eta_{\max}$ in a conical amplifier of length 10 m amount to $\sim 60\,\% - 70\,\%$.

For all conical amplifiers considered by us, the efficiency of energy extraction attains the maximum value $\eta_{\max} \approx 0.52$ for $L = 0.5 - 1.5$ m (see Fig. 2). This is due to the fact that the signal at the amplifier input $\Phi(0) = 1 < \Phi_{\text{opt}}$. If the equality $\Phi(x) = \Phi_{\text{opt}}$ is satisfied at a certain distance from the amplifier input, the value of $\eta(L)$ starts decreasing. For small values of x_0 ($x_0 = 10$ cm), the behaviour of $\eta(L)$ is more complicated (see Fig. 2).

Let us analyse the behaviour of the functions $\eta(L)$ and $\Phi(L)$ in the vicinity of the cone vertex for small distances x_0. This problem is important for an analysis of the intensity of the amplified spontaneous emission (ASE). It follows from Eqn (2) that, for small x_0, the radiation intensity can decrease near the input aperture of the cone. Assuming that $\mathrm{d}\Phi/\mathrm{d}x|_{x=0} < 0$, we obtain

$$x_0 < 2\left\{g_0[1 + \Phi(0)]^{-1} - \alpha_0\right\}^{-1}. \tag{9}$$

According to (9), the distance $x_0 < 26$ cm for $\Phi(0) = 1$, while for $\Phi(0) = 10$, we have $x_0 < 600$ cm. If condition (9) is satisfied, the radiation intensity Φ of a conical amplifier first decreases with increasing the amplifier length due to 'rapid' expansion of the light beam cross section, and then increases. In a cylindrical amplifier with $\Phi(0) < \Phi_{\max}$, the radiation intensity can only increase continuously with the amplifier length.

Thus, the efficiency of energy extraction $\eta(L)$ in the vicinity of the input aperture of the cone may either increase or decrease. A decrease in the value of $\eta(L)$ near the cone vertex leads to a strong increase in the gain in this region and to a simultaneous increase in spontaneous emission noise from this region. For a part of a conical amplifier of length $L' = 50$ cm with the parameters $x_0 = 1$ cm, $\beta = 6.5^\circ$ $S_0 \approx 0.01$ cm^2) for $\psi(0) = 1$, the gain $G(L') = \psi(L')/\psi(0) \approx 1200$ (the maximum gain for a cylindrical amplifier under identical conditions is $G_{\max} = \Phi_{\max}/\Phi(0) = 12.8$). This imposes limitations on the input aperture diameter of the conical amplifier. In the case when the radiation intensity Φ near the input aperture of the cone is noticeably smaller than unity, it is necessary to analyse the effect of ASE in this region on the beam divergence of the conical amplifier.

3. Spontaneous emission noise amplification in a conical amplifier pumped by a travelling wave

Consider first the behaviour of the intensity I_{sp}^- of the amplified spontaneous radiation propagating from the cone base to the vertex. The specific power of spontaneous noise is given by [4]

$$W_{\text{sp}} = I_{\text{s}} g_0 \frac{\tau^*}{\tau_{\text{sp}}} \frac{1}{1 + \Phi}, \tag{10}$$

where $\tau^* \approx 0.33$ ns is the excited-state lifetime taking into account quenching collisions and $\tau_{\text{sp}} \approx 6$ ns is the spontaneous lifetime. The spontaneous noise intensity at the cone vertex is given by

$$I_{\text{sp}}^- \approx \int_0^L \frac{G(x) W_{\text{sp}}(x) S(x)}{4\pi (x + x_0)^2}\,\mathrm{d}x$$
$$\approx I_{\text{s}} g_0 \frac{\tau^* S(0)}{\tau_{\text{sp}} \Phi(0) 4\pi x_0^2} \int_0^L \frac{(1 + x/x_0)^2}{1 + \Phi^{-1}}\,\mathrm{d}x. \tag{11}$$

In the case of travelling-wave pumping of the conical amplifier (the pump pulse duration $t_\gamma \ll 2L/c$), the amplification length of spontaneous noise $L_{\text{sp}} = t_\gamma c/2$. Putting $t_\gamma = 6$ ns, we obtain $L_{\text{sp}} = 90$ cm. Since we are interested in the case when $x \gg x_0$, we can approximately assume that $1/(1 + \Phi^{-1}) \approx 3x/L_{\text{sp}}$ (Fig. 3) and $(1 + x/x_0) \approx x/x_0$. By integrating expression (11), we obtain

$$I_{\text{sp}}^- \approx I_{\text{s}} g_0 \frac{0.037 \tau^* L_{\text{sp}}^3 \beta^4}{\tau_{\text{sp}} S(0) \Phi(0)}. \tag{12}$$

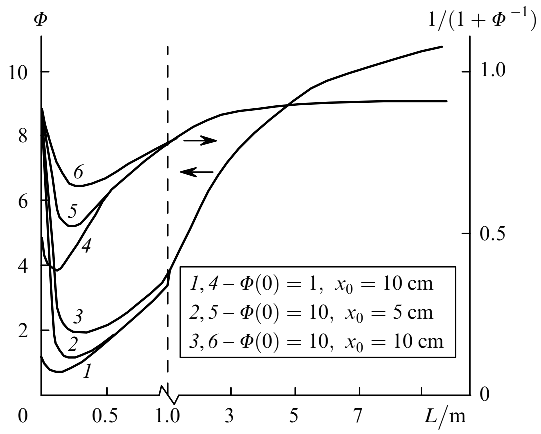

Figure 3. Dependence of the radiation intensity $\Phi = I/I_{\text{s}}$ from a conical amplifier and the function $1/(1 + \Phi^{-1})$ on its length L for different values of $\Phi(0)$ and x_0.

For our estimates, we assume that the critical intensity of spontaneous noise is $I_{\text{cr}}^- \approx I_{\text{s}}/3$. A further increase in the spontaneous noise intensity leads to a change in the useful signal intensity $\Phi(x)$. Taking this into account, we obtain from relation (12) the following limitation on the area of the input aperture of a conical amplifier, for which the amplified spontaneous noise starts absorbing a noticeable part of the stored energy:

$$S(0)\Phi(0) \geqslant 0.11 g_0 \left(\frac{t_\gamma c}{2}\right)^3 \frac{\beta^4 \tau^*}{\tau_{\text{sp}}}. \tag{13}$$

Putting $\beta = 0.1$ rad and $L_{\text{sp}} = 90$ cm, we find from condition (13) that $S_0 \geqslant 0.078$ cm^2 (accordingly, $x_0 \geqslant 3.2$ cm and $d_0 \geqslant 3.2$ mm) for $\Phi(0) = 1$ and $S_0 \geqslant 0.078$ cm^2 ($x_0 \geqslant 1$ cm and $d_0 \geqslant 1$ mm) for $\Phi(0) = 10$. Considering that the radiation intensity decreases near the cone vertex for small diameters of the input aperture, only the case when $\Phi(0) \geqslant 10$ can be regarded as acceptable. Thus, the minimum diameter of the input aperture of the cone amounts to ~ 1 mm for $t_\gamma \approx 6$ ns.

For the case considered above, the beam divergence at the output of the conical narrow beam former is $\theta \approx d_0/L = 10^{-4}$ rad. It follows from condition (13) that by decreasing pump pulse duration t_γ, we can realise stable operation of the conical amplifier even for lower input energies (accordingly, for smaller diameters of the input aperture).

The minimum diameter of the input aperture of the cone apparently amounts to 1 – 2 mm ($d_0 = 1$ mm corresponds to $t_\gamma \approx 6$ ns). This is due to the fact that, first, the condition $I < I_s$ may hold due to a 'rapid' increase in the light beam cross section in the vicinity of the input aperture of the conical amplifier (Fig. 3), and the beam divergence will not be determined by the useful signal alone any longer. Second, the coupling aperture may be covered by the plasma propagating from the surfaces of the diaphragm. In addition, a false signal of scattered radiation may also appear due to incomplete absorption of radiation by the side face of the cone in the vicinity of the input aperture. Thus, the maximum gain of a conical amplifier pumped by a travelling wave is $G_{\max} \leqslant \Phi(L)S(L)/[\Phi(0)S(0)] \approx S(L)/S(0) \approx (L\beta/d_0)^2 \approx 10^6$.

Consider now the steady-state operation of a conical amplifier ($t_\gamma \geqslant 2L/c$). In this case, the length $L_{\rm sp}$ of the spontaneous noise amplification region coincides with the cone length L. Putting $1/(1+\Phi^{-1}) \approx 0.9$ and $(1 + x/x_0) \approx x/x_0$, we obtain from relation (11)

$$I_{\rm sp}^{-} = I_s g_0 \frac{0.015\tau^*\beta^4 L^3}{\tau_{\rm sp}\Phi(0)S(0)}. \qquad (14)$$

For our estimates, we choose the critical intensity $I_{\rm cr}^{-}$ of spontaneous noise for which the formation of the collimated radiation is violated equal to $\sim I_s/3$. Using relation (14), we obtain

$$S(0)\Phi(0) \geqslant 0.044 g_0 \frac{L^3\beta^4\tau^*}{\tau_{\rm sp}}. \qquad (15)$$

For $L = 10$ m and $\beta = 0.1$ rad, we have $S(0)\Phi(0) \geqslant 44$ cm^2. In the steady-state operation mode, the required signal intensity at the amplifier input is $\Phi(0) \approx 1$ since, in accordance with inequality (9), the condition $\Phi(x) \geqslant 1$ holds in this case in the entire volume of the conical amplifier. Consequently, we obtain $d_0 \approx 7.5$ cm and the gain

$$G_{\rm st} \leqslant 10.8 \frac{S(L)}{S(0)} \approx 10.8\left(\frac{L\beta}{d_0}\right)^2 \approx 1920.$$

Thus, the gain of a conical amplifier in the steady-state operation mode is approximately 1/500 of the gain for the travelling-wave pumping with a pulse duration ~ 6 ns. If we take into account the backward scattering from the output mirror of the conical amplifier, the actual steady-state gain will be slightly lower. Since the gain of a cylindrical amplifier amounts approximately to 12.8, the advantages of conical amplifiers over cylindrical amplifiers in the steady-state mode are obvious: $G_{\rm st}^{\rm con}/G_{\rm st}^{\rm cyl} \approx 150$. Since the output energy $E_{\rm out}$ is proportional to t_γ, the steady-state operation of a conical amplifier can be used for obtaining high output energies. In this case, however, a considerable input energy is required ($E_{\rm in} \approx 30$ J for $t_\gamma = 66$ ns).

An increase in the light beam energy in the target chamber can be attained by increasing the pump pulse duration, but the energy density of optical radiation at the target decreases in this case. In accordance with condition (13), the breakdown in the formation of directed radiation can be prevented by making the input cone aperture diameter d_0 (and, hence the diameter of the light beam at the target) proportional to $t_\gamma^{1.5}$.

An analysis of the behaviour of the intensity $I_{\rm sp}^{+}$ of the ASE propagating from the vertex to the base of the cone proved that it is much lower than the intensity of the desired signal $I(x)$ determining the divergence of radiation in the entire active volume. Thus, the breakdown of the stable operation of a conical amplifier is associated with the development of spontaneous noise of intensity $I_{\rm sp}^{-}$. Under the condition $I_{\rm sp}^{-} \sim I_s$, the breakdown in the desired signal amplification takes place at the cone vertex, and the divergence of radiation emerging from the cone is not determined by the diameter of the coupling aperture.

4. System of focusing radiation from conical amplifiers at a target

The focusing of radiation emerging from a conical amplifier at a target, which was described in Ref. [1], has a number of obvious disadvantages. For example, the location of the chamber with the target in the active volume leads to a $\sim 30\,\%$ energy loss due to shadowing of the light beam. In addition, it is impossible to transport optical radiation from other conical amplifiers to the target, which makes it impossible to increase the energy of laser radiation at the target by using several amplifiers. For large diameters of the cone base and for the spherical mirror diameter D (e.g., $D \approx 2$ m), the size of the focusing spot increases due to spherical aberrations by approximately 2 mm, according to estimates. Taking into account the diameter of the input aperture of the cone (~ 1 mm), we find that the spot diameter is ~ 3 mm.

These drawbacks considerably complicate experiments with the focusing of radiation at the target with the energy required for initiating LIF ($\sim 10^6$ J). In this connection, a multimodule scheme with elliptical mirrors at the output of conical amplifiers was proposed for LIF in Ref. [6], which is free of the above-mentioned drawbacks and facilitates the LIF experiments to a considerable extent.

Fig. 4 shows the schematic of such an experiment with focusing of radiation from ten identical conical laser modules at a target with the help of elliptical mirrors. Each conical laser module is separated from the volume of a conical vacuum light guide by a quartz plate. The vacuum light guide is connected with the chamber containing the target. The axes of all identical conical laser modules and light guides lie on two conical surfaces whose axes are aligned and pass through a gamma-radiation source and the target, and their vertices coincide with the gamma-radiation source and with the target. In this case, the radiation emitted by the conical amplifiers reaches the target simultaneously, ensuring the automatic synchronisation of all laser beams only due to identical geometry of the arrangement of all elements of the scheme.

The extraction of the chamber with the target from the cone volume to the zone protected from the direct action of penetrating radiation considerably facilitates the recording of the laser plasma parameters and makes the access to the target more convenient. An important factor is the decrease in the energy density of luminous flux at the surface of the elliptical mirror and quartz glass (approximately by half) as compared to the version in which the chamber with the target is located in the active volume of the laser module. The elliptic mirror is used to form the image of the input aperture of the cone at the target, the diameter of the light beam at the target being equal to the diameter of the input

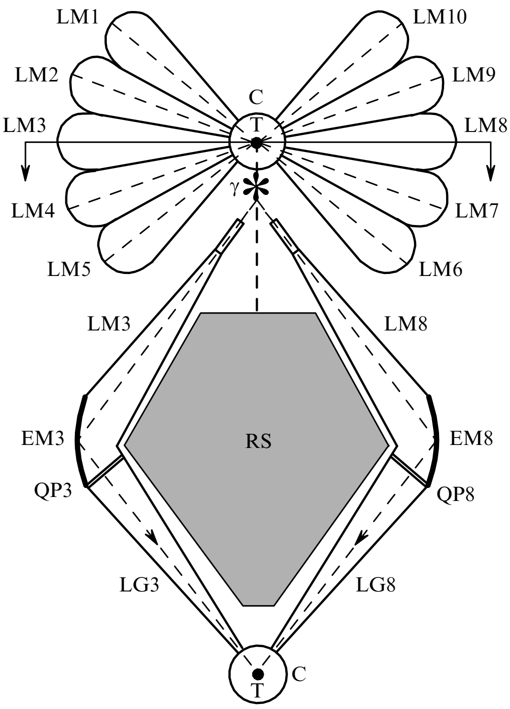

Figure 4. Schematic of an experiment on the compression of a target by radiation emitted by gamma-ray pumped excimer lasers: LM1–LM10 are conical laser modules, EM3 and EM8 are elliptical mirrors, QP3 and QP8 are quartz plates, RS is radiation shielding, LG3 and LG8 are vacuum light guides, C is the chamber, and T is the thermonuclear target.

aperture of the cone (1 – 2 mm). The use of a lens instead of the quartz plate would make it possible to reduce the focusing spot diameter if required. According to estimates, the focusing quality does not deteriorate if small (200 $\times$ 200 mm) identical fragments with elliptical surface are used instead of a one-piece elliptical mirror.

In conical formers of low-divergence beams, interference phenomena that may lead to a nonuniform distribution of radiation power density in the focal plane of the focusing system are absent due to the 'nonresonator' formation of light beams. Radiation can conveniently and easily be directed to the target; for adjustment, the illumination of the input aperture of the cone by diffuse light from a lamp (the optical system must form the image of the coupling aperture at the target). In a conventional laser system using an MO with an optical cavity and a number of optical elements for dividing its radiation among the inputs of amplifying stages, some complications arise during radiation focusing at the target. The proposed laser system also ensures a highly radiation contrast at the target due to the absence of an autonomous MO. Therefore, the laser system considered in this paper and intended for LIF has a much simpler construction than a conventional system. Its working off requires only an analysis of the conical laser module and light guide.

5. Conclusions

The conditions required for the formation of narrow beams from lasers pumped by gamma rays are considered. The estimates show that the divergence of the radiation emitted by an excimer laser based on the conical beam former proposed by us may be approximately 10^{-4} rad.

Conical narrow-beam formers can also be used upon pumping the active medium by an electron beam, microwave radiation, optical radiation, and a travelling wave in electric-discharge lasers.

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