A Powerful Laser Setup and Investigation of the Efficiency of High Temperature Heating of a Plasma

N. G. Basov, O. N. Krokhin, G. V. Sklizkov, S. I. Fedotov, and A. S. Shikanov

Submitted July 26, 1971

Zh. Eksp. Teor. Fiz. **62**, 203–212 (January, 1972)

An experimental laser setup for high temperature heating of a solid target is described. A powerful neodymium glass laser is set up which produces controllable pulses with durations between 2 and 16 nsec and a radiation energy of 600–1300 J. An electro-optical shutter controlled by a discharge gap with laser ignition is employed for formation of the light pulse. The contrast of the output radiation is $\sim 10^{-7}$. The radiance is 3×10^{16} W/cm² 3×10^{16} W/cm² ·sr. The mean irradiance at the target surface reaches 10^{16} W/cm². The maximum output energy of the laser is found to decrease with reduction pulse duration. Preliminary experiments are carried out on heating of a spherical polyethylene target. Ultra-rapid photography with a ruby laser ray is used for diagnostics of the heated plasma. The energy absorbed by the plasma is determined on the basis of the velocity of the spherical shock wave produced as a result of expansion of the target in the gas. In our experiments this energy for a pulse duration of 2 nsec is ~ 300 J. The results and promising lines of investigation are discussed.

At the present time, neodymium-glass lasers operating at nanosecond durations are widely used for plasma heating and research.[1-5] As a rule, the active elements in such lasers are arranged in tandem and their output constitutes a single light beam. The maximum energy of a neodymium laser is limited by the strength of the glass ($\sim$10 J/cm²[3]). The hitherto known experiments on plasma heating were performed at energy levels 10–100 J, this being caused to a considerable degree by the small cross sections of the active medium. In addition, in some cases it is advantageous to use spherically-symmetrical heating of the target. Such problems include investigations at strong spherical explosions, cumulative phenomena,[5] and heating of a small particle in a magnetic field for the purpose of plasma injection into a thermonuclear trap.[4] It is difficult, however, to obtain uniform irradiation of a target in the form of a sphere by using a single beam.

To increase the energy obtained with active elements of 45 mm diameter, and also to produce spherically-symmetrical heating conditions, we have developed a powerful laser setup (PLS) in which a system of "stepwise" amplification of the light pulse is used, with series-parallel arrangement of the active elements.[1)] The use of nine output beams makes it possible to increase by the same factor the maximum energy at the same rod diameter.

The results of the present investigation make it possible to carry out preliminary research and to point to definite ways of using laser radiation for plasma heating for thermonuclear purposes, since the radiation energy absorbed in the plasma was of the order of 10^3 J and greatly exceeded the energy of the presently known setups.

1. SCHEME OF POWERFUL LASER SETUP

The PLS scheme is shown in Figs. 1 and 2. To ensure maximum energy density at the output of each amplification stage, we used a series-parallel arrangement of the stages. To standardize the optical elements, the power amplification stage (PAS), the diagram of which is shown in Fig. 2, makes use of identical rods of 4.5 cm diameter, pumped-section length 60 cm, and end faces cut at the Brewster angle. The rods are cooled with a liquid coolant that serves simultaneously as a light filter. In practice, a 4.5 cm diameter is the limit for rods with 2% neodymium concentration. To increase the diameter it is necessary to reduce the neodymium concentration.

Let us consider, stage by stage, the operating principle of the PLS. Figure 1 shows a diagram of the Q-switched laser and the system of the pre-amplification stage (PS). The laser pulse is shortened with the aid of a shutter controlled by a discharge gap actuated by a light beam. The pulse-shortening shutter, as shown by the measurements, ensures a contrast of 5×10^{-5}. The duration in the shape of the light pulse passed the shutter were determined by the parasitic parameters of the discharge gap and of the shaping line, which is switched by this gap.[7] Oscillograms of a pulse-shaping system made it possible to operate the PLS in four regimes, with pulse durations 2, 4, 8, and 16 nsec.

After the rectangular pulse is shaped, the radiation is amplified by a pre-amplifier stage consisting of four amplifiers in tandem, with rod diameters 1.5, 2, 3, and 4.5 cm. The light beam passes through the first rod, which is 24 cm long, three times. Figure 4 shows plots of the energy of the amplified pulse as a function of the length of the optical path traversed in the active medium. The points give the light energy in the pulse after each amplifier. When the driving pulses were 8 and 16 nsec long, the pumping in the first amplifier of the PS was specially reduced to protect the rod against damage. The pulse shape was measured after the first PS amplifier. Amplification deformed the pulse shape somewhat, but the effective duration remained approximately the same.

After passing through the PS, the laser beam enters the PAS, where it acquires the main energy, in spite of the relatively low gain ($\sim$10). The PAS consists of two successive stages. In the first, the beam is divided into three parts, each of which, with suitable decoupling, is

[1)]Mead[6] split ruby-laser radiation into 12 beams which were subsequently amplified. All the beams, with a total energy 2 J, were then focused on a target to produce a spherical shock wave.

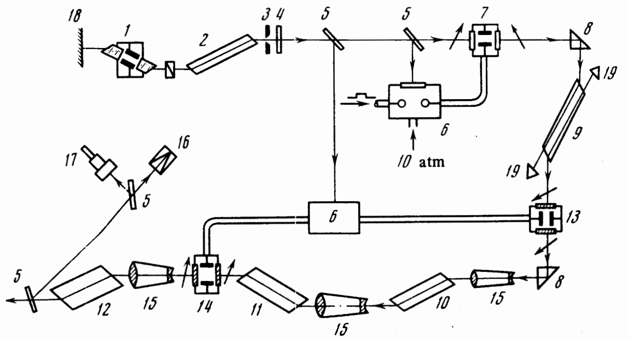

FIG. 1. Diagram of driving laser and of the pre-amplifier stage (PS): 1) Q-switch, 2) laser active element, 3) diaphragm, 4) output mirror, 5) diverting plates, 6) laser-actuated discharge gaps, 7) shaping shutter, 8) total internal reflection prisms, 9–12) active elements of amplifiers, 13, 14) decoupling shutters, 15) telescopes, 16) calorimeter, 17) coaxial photocell, 18) dielectric mirror, 19) prisms.

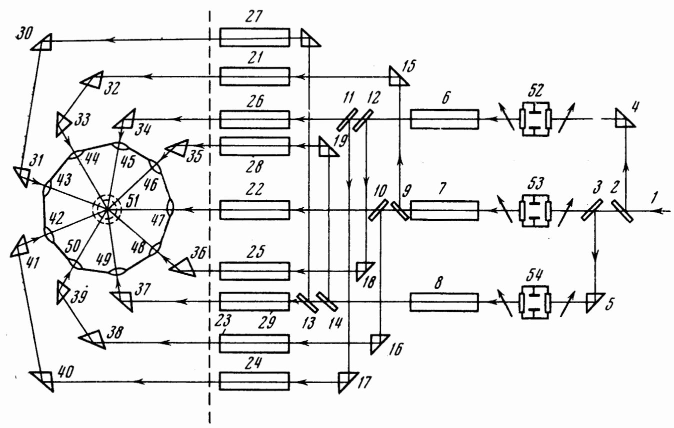

FIG. 2. Diagram of power amplification stage (PAS): 1) laser beam from pre-amplifier, 2, 3) beam-splitting elements, 4, 5) total-internal-reflection prisms of the division system of the first PAS stage, 6–8) active elements of first PAS stage; 9–14 and 15–20) beam-splitting elements and total-internal reflection prisms of the division system of the second state, 21–29) active elements of the second PAS stage; 30–41) beam-joining system, 42–45) focusing lenses, 51) target, 52–54) decoupling shutters. The calorimeters and coaxial photocells are not shown in the diagram. Optical delays (not shown in the diagram) were used in some beams to compensate for the optical path differences.

amplified by one rod. In the second PAS stage, each beam is again divided into three and amplified anew (Fig. 2).

After the amplification, all nine beams were guided with the aid of a prism convergence system to focusing lenses located in the walls of a spherical closed chamber of 100 mm radius. The diameter of the caustic of the lens was 50 μ. Thus, the system for focusing and converging the beams ensured practically uniform irradiation of a spherical polyethylene target of 0.1–0.5 mm diameter. The radiation energy and the shape of the light pulse were monitored at different points of the PLS with the aid of calorimeters and coaxial photocells, the pulses from which were registered in each experiment.

To photograph the high-temperature processes occurring when the target is heated, we used a procedure of super-high-speed laser photography in the light of a ruby laser. The procedure is described in [8], but we decreased the frame exposure to 0.4 nsec[9] and increased the number of frames to 7. The ruby laser was synchronized with the PLS by means of coaxial and optical delay lines.

2. EMISSION PARAMETERS

At an energy of 0.8 J, we were able to realize in a laser controlled by a Kerr cell a divergence $\alpha = 1.8\lambda/d$ at half the intensity (λ is the wavelength of the laser emission and d = 4 mm is the diameter of the output diaphragm). Such a divergence corresponds to four or five angle modes. The radiation brightness was 3×10^{14} W/cm^2-cm.

To decrease the losses in the resonator during the generation time, the Kerr shutter operated in the voltage-off regime. The required loss in the resonator during the pumping time was produced by applying to the shutter a millisecond voltage pulse, ensuring, at two passes of the light through the shutter, a path difference of $\lambda/2$ between the beams with polarization-vector components parallel and perpendicular to the field. The Q-switching was effected by turning off the electric potential. The transmission of the shutter was then determined mainly by two factors: the loss to Fresnel reflection and the absorption in the nitrobenzene. The use of windows and polarizers with surfaces inclined at the Brewster angle to the beam axis has made it possible to reduce the resonator losses to a value not exceeding 5% for two passes.

The table lists the energy characteristics of the PLS at the different amplification stages for different durations. E_4 and E_5 are respectively the values of the energy (in J) at the PS output in one beam and the total energy of the nine beams at the PAS output; the energy measurement accuracy is about 10%. B_5 is the brightness at the output of the PAS, K the total energy gain, q the flux density on the target, and $k = E_5/E_C$ the efficiency of the PLS relative to the electric energy of the capacitor bank.

It is seen from the table and from Fig. 4 that when the pulse is shortened from 16 to 2 nsec the energy is decreased by approximately one-half. The spatial distribution of the intensity and the coherence characteristics of the beam remain practically unchanged. The mechanism whereby the energy is decreased when the pulse duration is reduced is still unclear. It can be assumed that at a duration of 2 nsec the lower nonradiative transition, whose lifetime is of the same order, becomes saturated. Preliminary data, however, show that when the duration is reduced to less than 1 nsec the decrease of the energy is by a factor of more than three compared with τ = 16 nsec. Furthermore, it follows from [3] that at a duration $\tau \approx 10^{-11}$–10^{12} the limiting laser energy, when a rod with 4.5 cm diameter is used

τ, nsec	E_4, J	E_5, J	$B \cdot 10^{-16}$, W/cm² sr	$K \cdot 10^{-4}$	$q \cdot 10^{-16}$, W/cm²	η, %
2	60	600	4.3	3	1.5	0.15
4	90	800	2.9	1.6	1	0.20
8	110	1000	1.8	0.9	0.6	0.24
16	140	1300	1.2	0.6	0.4	0.30

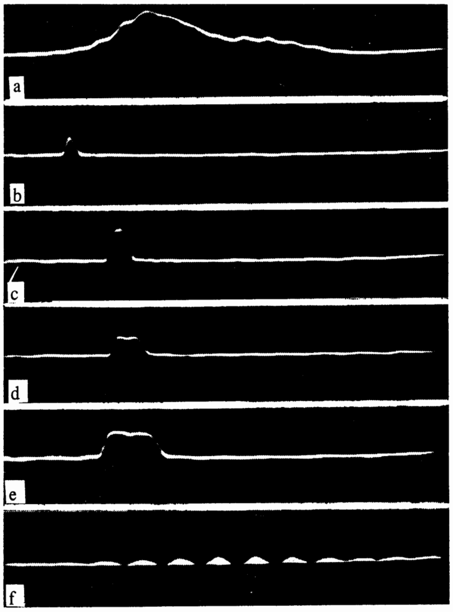

FIG. 3. Emission pulses: a) from generator, b–d) past the shaping shutter and the first amplifier with the PLS operating at 2, 4, 8, and 16 nsec, respectively; e) 10-nsec time pips.

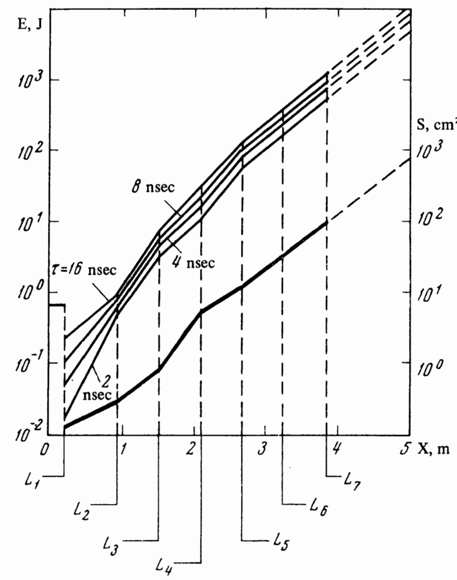

FIG. 4. Light-pulse energy vs. length of the optical path X in the active medium for different pulse durations. The curve marked S is a plot of the beam area inside the rod at the output of each amplification stage. The numbers of the curves show the duration of the laser pulse in nsec. The lengths L_{1-7} correspond respectively to output-rod diameters 1.2, 1.2, 2, 3.5, 4.5, and 4.5 cm, and to beam diameters 0.4, 0.6, 1, 2, 4.5, 4.5, and 4.5 cm.

at the output, is 20 J, which is one-seventh the value at τ = 16 nsec. It should be noted that in the case of ultrashort pulses the energy decrease can result from nonlinear losses in the active medium[3] and in the saturating filters.

It is important that such a multiple-beam laser with a complicated system for separating and amplifying the beam is quite critical to any type of parasitic feedback. To eliminate coupling between the stages, we used electro-optical Kerr shutters. Pockels shutters have a lower reliability, owing to the possible damage by optical overloading. This pertains, in particular, to large-aperture decoupling shutters. In the present PLS, the generator is decoupled from the remaining stages by a shutter that simultaneously shapes the light pulse. Other shutters decouple the amplifying stages, as shown in Figs. 1 and 2. As a result of such a system of shutters between the amplification stages, the energy of the background of spontaneous generation and radiation, corresponding to the initial generation pulse, does not exceed 10^{-4} of the energy of the useful pulse.

The most dangerous from the point of view of excitation of the PLS is reflection of radiation from the target located in the focus of the nine beams. The use of saturable filters in the output stages of the PLS is not effective, owing to the nonlinear losses in the nitrobenzene and owing to the fact that the optical characteristics do not remain constant in time. The presence of a large number (~10) of dense filters has led to excitation of the laser in a regime of repeated giant pulses, with energy of several hundred Joules in each pulse. Such an excitation, as a rule, inflicts severe damage on the optical elements.

The optimal conditions for each PLS were obtained by placing three electro-optical decoupling devices in the beams past the first splitting in the PAS. The presence of polarizers in the form of stacks limited the losses in the shutters to not more than 10%. Special Kerr cells with large-aperture diaphragms, ~4 cm, and with short optical path lengths have made it possible to reduce to a minimum the loss due to self-focusing and stimulated scattering in the nitrobenzene.

Nine beams of approximately equal intensity are produced at the PAS output. The optical path of each beam is adjusted by optical compensators, accurate to 1 mm, meaning that all the light pulses arrive at the target within $\sim 3 \times 10^{-11}$ sec. We note that measurement of the temporal coherence of the driving laser past the shaping shutter in the PS yielded a value of ~5 mm. Thus, differences in the arrival times of the pulses at the target hardly affect the coherence of the beams.

The divergence of all the PLS beams was 3×10^{-4} rad. In spite of the fact that the divergence at the output was smaller by several times than the divergence of the driving laser, it did not vary in proportion to the light-beam diameter, so that it was worse by almost one order of magnitude relative to its diffraction limit ($\sim 3 \times 10^{-5}$) at the output of the PS. Such a relative deterioration of the divergence occurred in spite of the use of high-grade telescopic systems to compensate for different distortions resulting from the uneven pumping of the neodymium rods.

As shown in [8], an important role is played in plasma heating by the contrast of the radiation (i.e., the ratio of the intensity of the useful signal to the maximum intensity of the background). In the present installation, owing to the use of the shutters described in [7,8] the contrast amounted to 10^7.

The focusing system ensured a flux density of 10^{16} W/cm^2 at the target in the case of a flat target, and 2×10^{15} W/cm^2 in the case of a spherical target. In the case of spherical irradiation of the target, the specific energy release rate in the heated plasma can reach 10^{18} W/cm^3, provided the radiation is completely absorbed by the target. For a target with 0.5 mm diameter, the experimentally attained rate of energy release is 5×10^{15} W/cm^3. The latter can be appreciably increased by using heavy targets of smaller dimensions.[10]

3. EFFICIENCY OF ENERGY SUPPLY TO THE PLASMA

The optical radiation of the PLS was focused on a spherical target whose dimension was chosen to satisfy the condition $r_0 = v\tau$, where v is the characteristic rate of expansion of the plasma at the temperature T. Assuming $T \approx 1$ keV and a heating duration $\tau \approx 2 \times 10^{-9}$ sec, we have for the target radius $r_0 \approx 2.5 \times 10^{-2}$ cm.

When the radiation is focused with the aid of optical elements, the loss to Fresnel reflection amounts to 25%. Measurements of the fraction of the radiation reflected from the target have shown that it does not exceed several per cent and can be neglected in the overall energy balance.

When the target is heated, it expands and becomes transparent to the heating radiation. It is therefore of considerable interest to determine the fraction of the absorbed radiation consumed in increasing the internal and kinetic energies of the plasma. Direct measurement of the absorbed energy, by using the radiation passing through the target, is difficult in the case of spherical irradiation with many beams, since radiation passing through a hot, inhomogeneous, and expanding plasma experiences strong refraction, and the beams overlap. We have measured the energy absorbed in the target by observing the gasdynamic expansion of the spherical shock wave in the residual gas during the later stages after the end of the laser pulse; this shock wave results from the expansion of the plasma. The motion of the shock wave can be described by the formulas used for a spherical instantaneous point explosion,[12] if the mass of the gas subtended by the shock wave becomes much larger than the mass of the heated target. In our case this occurs at a shock-wave radius $R \approx 20r_0$.

The law governing the motion of the shock-wave front for a point spherical explosion in a homogeneous atmosphere is given by the expression

$$R = [a(\gamma)Et^2/\rho_0]^{1/5}, \tag{1}$$

where $a(\gamma)$ is a coefficient that depends on the adiabatic exponent, $a(\gamma) \lesssim 1$ in our case; E is the energy of the explosion, equal to the absorbed optical energy of the laser, if we neglect the radiation of the hot plasma; ρ_0 is the density of the unperturbed matter.

Figure 5 shows a seven-frame shadow photograph of a shock wave produced in air at a pressure of 15 Torr. Owing to the spherical irradiation of the target, the shock wave has good spherical symmetry. The shock wave is formed within approximately the first 50 nsec.

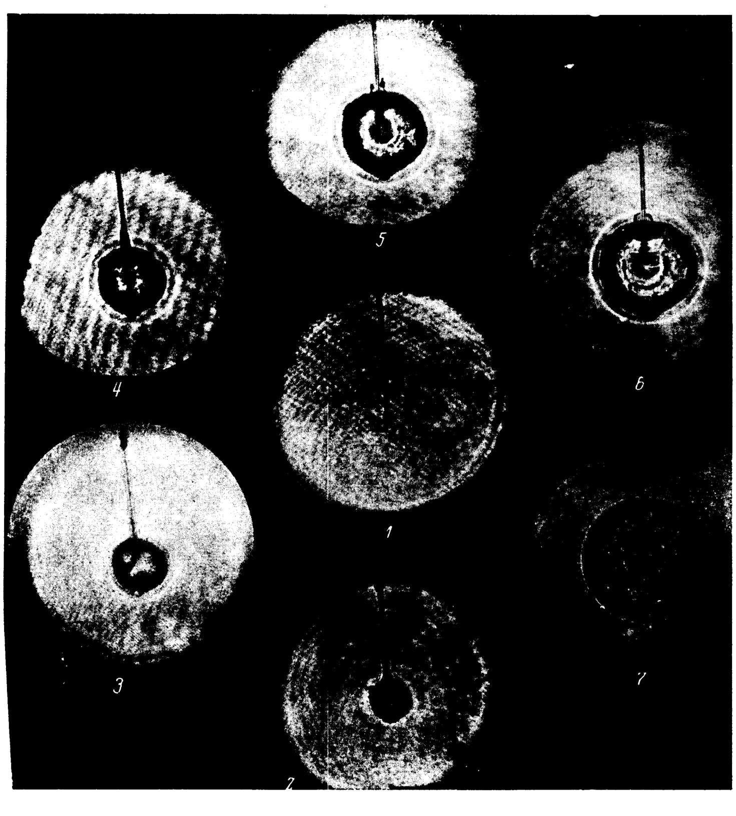

FIG. 5. Shadow photographs of shock wave. The instants of exposures of frames 1–7 correspond to delays of 2, 20, 45, 70, 140, 210, and 460 nsec, respectively, relative to the start of the heating. Polyethylene target, $r_0 = 2.5 \times 10^{-2}$ cm, mounted on the tip of a needle 10^{-3} cm thick. Frame diameter 57 mm.

Such a long formation time, compared with the heating time (~ 2 nsec), is due to the large density of the target, which acts like an expanding piston in comparison with the density of the surrounding atmosphere. In addition, the radiation of the heated plasma during the earlier stage is in the region of the far "ultraviolet" and soft x-rays, which are strongly absorbed in air. The character of the expansion of the heated matter at $t \lesssim 50$ nsec is therefore greatly influenced by radiation processes and by electronic thermal conductivity, and changes into pure gasdynamic motion only during the later stages. This is the cause of the strong smearing of the wave front on the first frames. A certain asymmetry in the wave shape can be due to ionization of the gas in the focus beams, and also to the asymmetry of the target irradiation.

Figure 6 shows the dependence of the shock-wave radius on the time for three experiments under the same conditions. The law governing the shock-wave front motion in the interval from 50 to 250 nsec corresponds to the spherical-explosion relation $R \propto t^{0.4}$. The same figure shows for comparison R-t diagrams calculated in accordance with formula (1) at explosion energies 10, 100, 350, and 1000 J for $a(\gamma) \approx 1$ ($\gamma \approx 1.29$). From the comparison of the theoretical curves with the experimental ones it can be concluded that the explosion energy in the experiment was ~ 300 J. This gives the minimum laser-radiation energy absorbed by the plasma during the course of heating. Part of the laser energy passes through the plasma without being absorbed, and part of the energy goes to radiation. Taking into account the losses in the optical elements, it can be concluded that the light energy incident on the target is 450 J, and not less than 70% of it is absorbed in the target.

After 250 nsec, the dependence of the radius on the time becomes $R \propto t^{0.3}$. This can be attributed to losses to recombination radiation, to which the plasma behind the shock-wave front is transparent in the time interval under consideration. It is clear from simple considerations that the radiation intensity is increased as a result of the increase in the volume and of the drop in the temperature of the heated gas, until the gas temperature behind the wave front decreases to a considerable degree so that the radiation intensity can be neglected.

We note that when the laser pulse duration is long, the target dimension must be increased if the energy input to the target is to be efficient. This is undesirable if high temperatures are to be obtained. In the case of shock-wave formation, however, such an increase of the target mass leads only to an increase in the time of shock-wave formation. During the later stages, the shock-wave parameters are determined by the laser energy. The fraction of the absorbed energy is then independent of the duration. Thus, the energy absorbed by a target of 3 mm diameter, at a 16 nsec duration and a laser radiation energy 1300 J, was ~ 700 J.

4. DISCUSSION OF RESULTS

As shown in a number of papers,[13] to produce a physically convenient thermonuclear reaction, when the light-radiation energy is equal to the reaction energy, the required laser-radiation energy is not less than 10^5–10^6 J at a duration 10^{-10}–10^{-9} sec. In the present investigation the light energy absorbed by the plasma was on the order of 10^3 J. Let us make a few remarks concerning the feasibility of obtaining an energy on the order of 10^5 J, at which it is possible to approach the threshold of a physically convenient thermonuclear reaction.

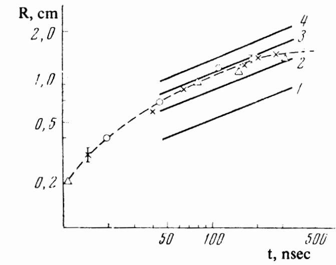

FIG. 6. Experimental time dependence of the shock-wave radius (dashed curve). The points O, X, and Δ correspond to three independent experiments at $\tau = 2$ nsec. The theoretical curves 1–4 correspond to explosion energies 10, 10^2, 3.5×10^2, and 10^3 J.

By approximating the curves of Fig. 4, we can estimate, with sufficient accuracy, the optical length of the active medium, which need be only 1.6 times larger than in the case of 10^3 J if each beam is split into three. This splitting of a beam into three is not optimal, and with suitable pumping and illuminator reliability splitting into five or six can be attained. This decreases the length of the active medium considerably. We see that the length of the active medium, even for 10^5 J energy, is small compared with that used in existing lasers. As seen from Fig. 4, the area of the active medium increases in proportion to the light energy. Recognizing that such a successive splitting and amplification increases the length of the active medium insignificantly, we can readily see that the volume of the active medium varies in proportion to the energy.

With respect to the efficiency, we note that in the given PLS, by a more optimal distribution of the electric supply and by choosing the suitable concentration, it is possible to increase the efficiency to 1%.

We note that the decrease of the output energy, and hence the efficiency, observed in the present study when the duration is decreased, cannot be definitely explained at present, since there are no lasers with adjustable pulse duration. This circumstance may be a serious obstacle in the construction of a thermonuclear setup, since the optimal pulse duration for a laser with energy 10^5 J is $\sim 10^{-10}$–10^{-9} sec. If the decrease of the energy is connected with saturation of the lower nonradiative transition, then the energy should not decrease by more than a factor of 2 when the duration is decreased to 10^{-10} sec. This premise, however, calls for a special experimental study.

In conclusion, it is our pleasure to thank I. M. Buzhinskiĭ, M. P. Vanyukov, S. K. Mamonov, and A. N. Khomyakov for useful consultations, and B. I. Belov, V. M. Groznov, I. M. Divil'kovskiĭ, A. A. Erokhin, D. V. Kovalevskiĭ, and B. V. Kruglov for help in preparing the capacitor bank and the supply circuits.

[1]N. G. Basov, V. A. Boĭko, V. A. Gribkov, S. M. Zakharov, O. N. Krokhin, and G. V. Sklizkov, Zh. Eksp. Teor. Fiz. **61**, 154 (1971) [Sov. Phys. JETP **34**, 81 (1972)].

[2]F. Floux, D. Cognard, L. Denoeud, G. Pior, D. Parisot, J. Bobin, F. Delobeau, and C. Fauguignon, Phys. Rev. A **1**, 821 (1970).

[3]N. G. Basov, I. Kertes, P. G. Kryukov, Yu. A. Matveets, Yy. V. Senatskiĭ, and S. V. Chekalin, Zh. Eksp. Teor. Fiz. **60**, 533 (1971) [Sov.

Phys. JETP **33**, 289 (1971)]; N. G. Basov, P. G. Kryukov, Yu. V. Senatskiĭ, and S. V. Chekalin, Zh. Eksp. Teor. Fiz. **57**, 1175 (1969) [Sov. Phys. JETP **30**, 641 (1970)].

[4]A. Haught, D. Polk, and W. Fader, Phys. Fluids **13**, 2841 (1970). C. Yamanaka. Progr. report VI Laboratory for Plasma and Quantum Electronics, Faculty of Engineering, Osaka University, Japan, 1970.

[5]N. G. Basov, O. N. Krokhin, and G. V. Sklizkov, Tr. Fiz. Inst., Akad. Nauk SSSR **52**, 171 (1970).

[6]S. W. Mead, Phys. Fluids **13**, 1510 (1970).

[7]N. N. Zorev, G. V. Sklizkov, S. I. Fedotov, and A. S. Shikanov, Preprint FIAN No. 56, Moscow, 1971.

[8]N. G. Basov, V. A. Gribkov, O. N. Krokhin, and G. V. Sklizkov, Zh. Eksp. Teor. Fiz. **54**, 1073 (1968) [Sov. Phys. JETP **27**, 575 (1968)].

[9]V. A. Gribkov, G. V. Sklizkov, S. I. Fedotov, and A. S. Shikanov, Prib. Tekh. Eksp. ,(4), 213 (1970).

[10]Yu. V. Afanas'ev, É. M. Belenov, O. N. Krokhin, and I. A. Poluéktov, Zh. Eksp. Teor. Fiz., Pis'ma Red. **13**, 257 (1971) [JETP Lett. **13**, 182 (1971)]; S. D. Zakharov, O. N. Krokhin, P. G. Kryukov, and E. L. Tyurin, Kvantovaya élektronika, No. 2, 102 (1971) [Sov. J. Quant. Electr. 1, 196 (1972)].

[11]N. G. Basov, V. A. Boĭko, S. M. Zakharov, O. N. Krokhin, and G. V. Sklizkov, Zh. Eksp. Teor. Fiz., Pis'ma Red. **13**, 691 (1971) [JETP Lett. **13**, 489 (1971)].

[12]V. P. Korobeĭnikov, N. S. Mel'nikova, and E. V. Ryazanov, Teoriya tochechnogo vzryva (Theory of Pointed Source Explosion), Fizmatgiz, 1961.

[13]O. N. Krokhin, in the book, Physics of High Energy Density, Academic Press Inc.-NY.-L., 1971; N. G. Basov and O. N. Krokhin, Vestnik AN SSSR **6**, 55 (1970); H. Hora, Laser Interaction and Related Plasma Phenomena, ed. by H. Schwarz and H. Hora, Plenum Press, 1971; P. P. Pashinin and A. M. Prokhorov, Zh. Eksp. Teor. Fiz. **60**, 1630 (1971) [Sov. Phys. JETP **30**, 883 (1971)].

Translated by J. G. Adashko
28