Experimental study of the acceleration of thin foils by high-power laser pulses

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It is shown that the principal physical processes which occur upon bombardment of thin films by high-power laser pulses in the light-flux density range 10^{13}–10^{14} W/cm^2 agree with the results of the two-dimensional hydrodynamical calculations which have been made. The maximum recorded velocity of the material on the back side of a bombarded aluminum foil of thickness 6 μm was $5 \cdot 10^6$ cm/sec for a laser-pulse energy 100 J. The theoretical value of the hydrodynamical efficiency reached about 5% in this case. (For a laser-pulse energy of about 100 J the kinetic energy of the accelerated portion of the target is 4.5–4.8 J.) In the investigated range of laser-radiation intensity no limitations on the heat flux in comparison with those predicted by the classical theory are observed. A strong effect of the x radiation of the plasma corona on the state of the accelerated part of the foil is observed. Analysis of the x-ray spectra indicates that under our conditions for a light-flux density of about 10^{14} W/cm^2 the number of "hot" electrons with effective temperature about 5 keV does not exceed 10^{-4} of the total number of electrons in the plasma corona.

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1. INTRODUCTION

In spite of substantial progress achieved recently in study of laser-induced thermonuclear fusion, the question of the minimum laser-pulse energy necessary for initiation of a self-maintaining thermonuclear reaction in the bombarded target remains essentially unsolved. Depending on the degree of optimism of the assumptions and target designs used in the calculations, estimates give values varying by two orders of magnitude from 200 kJ up to 20 MJ. This uncertainty is explained by the lack of sufficiently clear ideas supported by experimental proofs regarding a number of basic questions of a physical nature, concerning the absorption of the radiation in the plasma corona, the heat transfer from the zone of absorption to the surface of the accelerated shell, the efficiency of acceleration, and the stability of the shell during the compression stage.

In the studies carried out with the apparatus which has been described in detail in a previous article,[1] the main emphasis was on study of the acceleration of the foils, measurement of the hydrodynamical efficiencies, and identification of the mechanisms of heat conduction in the laser plasma. An effective means of study of the variety of processes occurring in the laser plasma was comparison of the obtained data with the results of numerical calculations based on one-dimensional and two-dimensional hydrodynamical programs, and carried out for the actual conditions of the experiment. On the one hand, the calculations permit improvement of the planning of the experiment and estimation of the region of variation of the measured parameters, and on the other hand comparison of experimental and theoretical information provides the possibility of checking how completely the various physical processes are taken into account in the calculation and how accurately and in what detail they are reproduced by the theoretical programs.

2. PARAMETERS OF THE APPARATUS AND METHODS OF MEASUREMENT

The experiments were performed with comparatively modest intensities of neodymium laser radiation on the surface of the irradiated target of about $(2-3) \cdot 10^{14}$ W/cm^2 (according to current ideas the optimum light-flux density for large-scale experiments on laser-induced fusion is 10^{14}–10^{15} W/cm^2). The energy of the laser pulse of duration 3.0 nsec was varied over the range 100–300 J. All investigations were carried out in a plane geometry, which greatly facilitates the measurements.

In our experiments the targets were thin metallic foils of various materials, organic films, and thin double-layer targets. In study of the motion of the plasma on the back side of the target and on the side of the incident laser pulse we used interference and shadow techniques. The region near the target was illuminated by a light beam split off from the main heating beam and converted to the second harmonic ($\lambda = 0.53$ μm).

Two detection arrangements were used. In the first version the detection was accomplished by an image converter operating in the slit-sweeping mode. In the second version the probing beam was split into five beams traveling at small angles to each other and successively passing through the investigated plasma with a time delay. The five frames were recorded on photographic film. A two-frame holographic arrangement was also used. To study the x-ray emission and the distribution of the sources of x radiation we used an eight-channel x-ray spectrometer employing pin diodes with bandpass and differential absorbers, a crystal spectrograph with spatial resolution, a pin-hole camera, and x-ray detectors with subnanosecond time resolution. The spectra of the fast electrons were analyzed with a magnetic analyzer located about 70 cm from the target. In each experiment we recorded the energy and shape of the incident laser pulse, the distribution of radiant intensity in the far zone, and the energy contrast of the laser system.

3. EXPERIMENTAL RESULTS AND DISCUSSION

In a series of experiments we demonstrated good agreement of the measured parameters of the plasma corona (temperature distribution, x-ray source dis-

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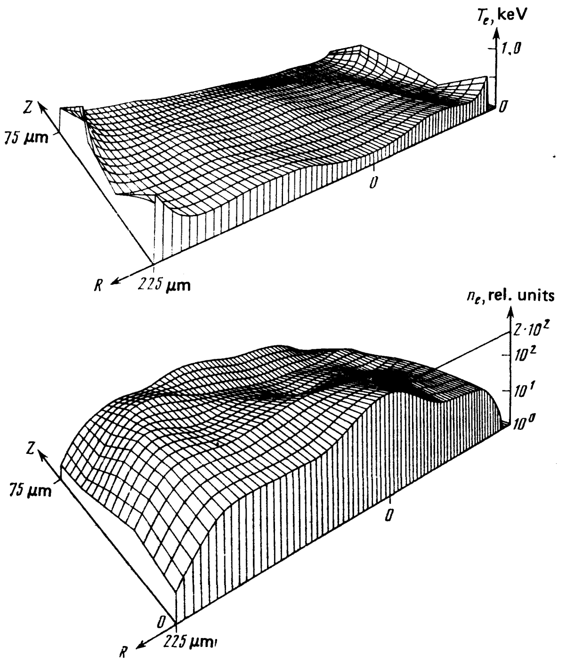

FIG. 1. Distributions of temperature and density constructed with automated processing of pin-hole-camera photographs by computer (aluminum target, $E=100$ J, $\tau=3.0$ nsec).

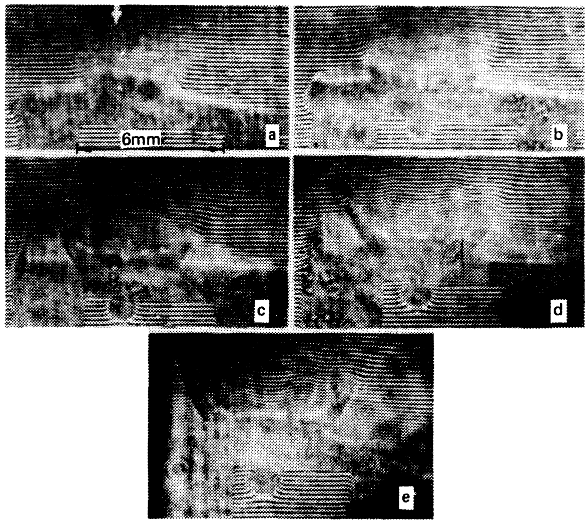

FIG. 2. Successive interference patterns of the plasma corona and the accelerated part of the aluminum foil on the back side of the target, obtained at times 4 nsec (a), 7 nsec (b), 10 nsec (c), 13 nsec (d), and 16 nsec (e) after the beginning of the bombardment (aluminum target of thickness 6 μm, $E=100$ J, $\tau=3.0$ nsec, frame exposure 0.5 nsec).

tribution, size of heated region, rate of expansion) with the results of two-dimensional hydrodynamical calculations. In these experiments aluminum foils of thickness 6, 10, and 20 μm with characteristic transverse dimensions much greater than the size of the focal spot were bombarded in an evacuated chamber by pulses of duration 3.0 nsec with energy about 100 J at light-flux densities up to $3\cdot10^{13}$ W/cm^2. In Fig. 1 we show the results of an automated analysis of pin-hole photographs of the plasma jet taken behind aluminum absorbers of thickness 3.2 and 5.6 μm (the bombarded target was aluminum, the light-flux density was about $3\cdot10^{13}$ W/cm^2, and the diameter of the openings in the pin-hole cameras was 30 μm). A series of successive interference patterns photographed by means of the five-frame arrangement under the same conditions (Fig. 2) demonstrates the dynamics of the spreading of the plasma corona and the acceleration of the material on the back side of the aluminum foil. The time interval between neighboring frames was 3.0 nsec. The exposure of a frame was less than 1 nsec. The measurements showed that at least 80% of the energy of the incident laser radiation is absorbed. The calculated distributions of the density and temperature in the plasma corona agree with the observed distributions within 10%.

In the hydrodynamical calculations at temperatures less than 0.15 keV we used the equation of state obtained on the basis of the Thomas-Fermi model with quantum corrections for $T\neq 0$, joined in the low-pressure region to experimental results on shock-wave compression (this equation of state was used for description of the "cold" accelerated part of the foil). For $t>0.15$ keV we used the equation for an ideal gas with allowance for the energy expended in ionization, which was calculated in the corona approximation (this equation of state was used for the description of the plasma corona). The energy loss from the corona by bremstrahlung and recombination radiation was calculated on the assumption that the corona was completely transparent. The thermal conductivity and the exchange of energy between electrons and ions were assumed to be "classical." We took into account the inverse bremsstrahlung of the laser, and the fraction of the energy of the incident radiation which reached the region with a critical density was "separated" in the immediate vicinity of the point with n_{cr}. The shape of the pulse and the intensity distribution in the focal spot were introduced into the calculations on the basis of experimental data.

From the methodological point of view an extremely important result of comparison of the experimental data with the calculations was the conclusion that refraction of the probing radiation by the density gradients of the plasma plays an important role.

In scanning the plasma corona produced by the high-power radiation, we observed a nontransparent region of appreciable size near the focus. At the edge of this region the plasma density is one and one-half or two times less than the critical density for the probing radiation ($\lambda=0.53$ μm, $n_{cr}\sim4\cdot10^{21}$ cm^{-3}). A convincing proof of the decisive role of refraction in forming the nontransparent zone is the observed increase in the size in this zone with decrease of the relative aperture of the objective in the detection system.[2] Calculations with allowance for refraction reproduce not only the size of the nontransparent zone but also its dynamics in time.

In the same experiments it was shown that the initial velocity of propagation of material on the back side of the target is inversely proportional to its thickness and depends on the energy density at the target. The maximum recorded velocity in bombardment of an aluminum foil of thickness 6 μm with a laser-pulse energy ~150 J reached $8 \cdot 10^6$ cm/sec, which agrees rather closely with the theoretical value. The delay in beginning of the motion of the material on the back side of the target relative to the beginning of the bombardment agrees with estimates of the time of propagation of a shock wave through the foil.

The diameter of the region occupied by the material set in motion on the back side of the target somewhat exceeds the size of the focal spot (about 400 μm). As can be seen from the characteristic bending of the interference fringes near the edge of the nontransparent zone (see Fig. 2), the leading edge of the expanding material is ionized. Analysis of the experimental data on the expansion of the accelerated portion of the aluminum foil, obtained by the interference method, leads to plasma temperature values ~10 eV. The boundary of the expanding zone of nontransparency on the back side of the target is greatly smeared. These facts are inconsistent with earlier calculations according to which the plasma temperature on the back side of the target under the conditions of our experiments should be no more than 2 eV, and the boundary of the nontransparent zone should be extremely sharp. However, when the heating of the accelerated part of the foil by nonequilibrium x radiation of the plasma corona was taken into account, the agreement between the calculations and experiment became satisfactory.

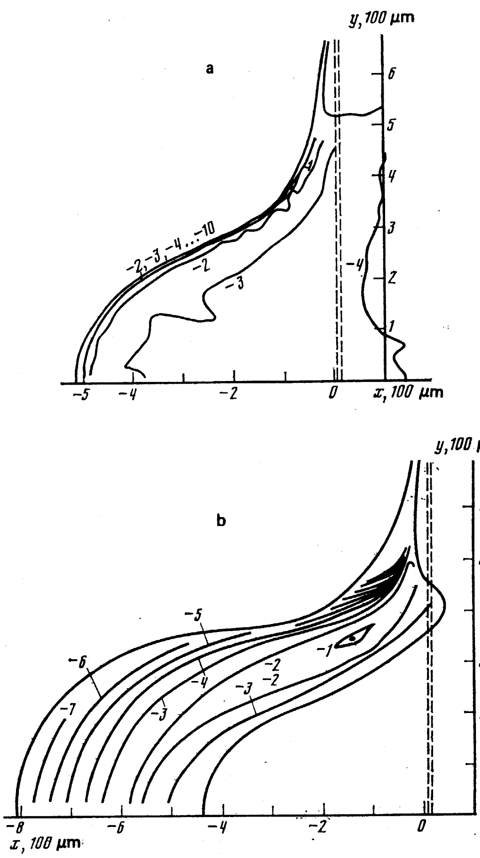

FIG. 3. Distributions of density in the accelerated part of an aluminum foil of thickness 6 μm bombarded by a laser pulse of duration 3.0 nsec with energy 100 J. The distributions were obtained in two-dimensional hydrodynamical calculations without (a) and with (b) allowance for the heating of the accelerated material by the x radiation of the plasma corona. The curves correspond to the indicated numerical values of $\log_2(\rho/\rho_{crit})$ for a wavelength of radiation $\lambda = 0.53$ μm at a moment of time $t = 11.8$ nsec.

By way of illustration we have shown in Fig. 3 density distributions on the back side of an aluminum target of thickness 6 μm calculated without (a) and with (b) allowance for heating of the accelerated material by x radiation of the plasma corona. It should be noted that the heating of the accelerated material of the target is not in doubt, but in addition to that of the nonequilibrium x radiation of the plasma corona a contribution to the heating can in general be made by suprathermal electrons. This fact must be taken into account in the calculations, especially in the case of higher light-flux densities bombarding the target than those used by us. Studies of the x radiation of the plasma corona have a direct bearing on this question.

In the range of light flux densities $5 \cdot 10^{13}-3 \cdot 10^{14}$ W/cm^2, there are distinctly visible in the x-ray spectrum two components corresponding to the presence in the plasma of thermal and suprathermal electrons (Fig. 4). Comparison with computer calculations carried out on the assumption that the distribution function of the plasma electrons consists of two Maxwellian components with different temperatures gives a hot-electron temperature about an order of magnitude greater than the principal (thermal) electron component ($T_{hot} \sim 4-5$ keV, $T_{cold} \sim 400-500$ eV). The fraction of hot electrons is small and amounts to about $(1-3) \cdot 10^{-5}$ of the total number of electrons; the number of hot electrons decreases rapidly with decrease of the light-flux density, and their temperature is practically unchanged by this.[3]

A question which is important for laser-induced fusion, and which is widely discussed in the literature,[4-6] is the question of limitation of the thermal conduction in the laser plasma. Possible reasons for the reduction of thermal conduction are discussed, including the generation of spontaneous magnetic fields and the development of ion-sound instabilities in the region between the zone of energy dissipation in the plasma corona and the

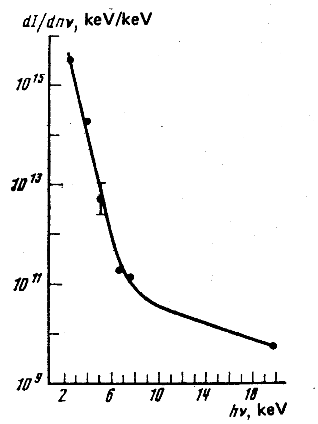

FIG. 4. Spectral distribution of intensity of x radiation of the plasma corona (aluminum target, $E = 140$ J, $\tau = 3.0$ nsec).

surface of the solid target. These authors offer the following arguments which should attest to substantial limitations of the heat fluxes: a significant part of the absorbed energy is carried away by fast ions; the rate of compression of spherical targets turns out to be below the calculated rate; the size of the region occupied by the hot plasma is less than expected; the thickness of the layer evaporated upon bombardment of thin planar targets turns out to be much less than the value which can be obtained on the basis of classical ideas of heat conduction.

It is quite evident that the first two points cannot be considered as proofs, as a result of their indirect nature. The facts presented can be explained without invoking the idea of a limitation of heat conduction. In regard to the third of the points discussed, in our experiments, which are similar to those carried out at the Naval Research Laboratory, the size and shape of the x-ray images of the plasma corona corresponded almost exactly to the intensity distributions of the laser radiation in the far zone. This is well illustrated in Fig. 5, where we have shown microphotographs of the x-ray images obtained by means of a pin-hole camera behind an aluminum absorber 10 μm thick, and distributions of the photographic density on a film placed in the focal plane of an objective focusing part of the outgoing laser beam. The nature of the distribution is due to the fact that the outgoing beam was split by means of optical wedges into two approximately equal parts. However, we cannot conclude from this comparison that the heat conduction is decreased as the result of any effect whatsoever. The fact is that the outflow of energy from the heat-dissipation zones occurs in the axial direction mainly as the result of the hydrodynamic motion of the plasma, and in the radial direction it occurs as the result of heat conduction. The efficiency of the two processes is approximately identical, and the axial dimensions of the region of intense x-ray emission are small as a result of the rapid expansion of the plasma. Therefore the spatial distribution of the x-ray sources reflects the distribution of the temperatures in a narrow layer of plasma with a concentration close to the critical value, and the size of the region emitting photons with energy greater than 2 keV does not exceed the size of the focal spot. (The authors of Ref. 4 did not take into account the hydrodynamic expansion of the plasma, and their conclusion that the heat conduction is not classical is unjustified.)

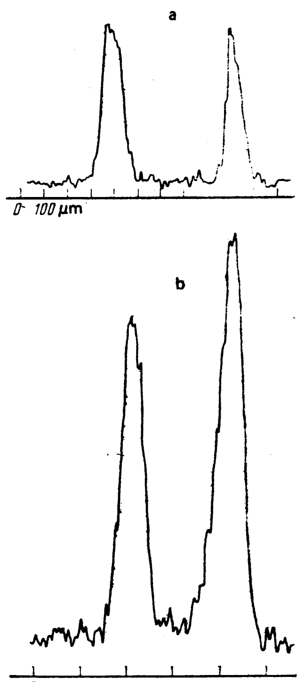

FIG. 5. Densitometer traces characterizing the distributions of intensity of the laser radiation at the focal spot (a) and sources of x radiation in the plasma corona (b) (aluminum target, $E = 100$ J, $\tau = 3.0$ nsec).

Since an exact solution of the three-dimensional problem is extremely laborious, modeling of the heat conduction in the plasma corona was accomplished by the following scheme. It was assumed that dissipation of energy occurs in two concentric rings with diameters much greater than the distance between them. (For average ring diameters 9950 and 10050 μm, respectively, we can assume with rather high accuracy that the energy dissipation occurs in two planar bands.) The intensity distribution inside each ring was specified in the form

$$Q(t,r)=Q_0 f(t)\exp\{-(r-r_{1,2})^2/h^2\},$$

where $r_{1,2}$ are the mean radii of the first and second rings, $f(t)$ is the shape of the pulse measured at the output of the laser system, and the quantity h was taken as 50 μm. In the model adopted, one-dimensional expansion of the plasma in the region between the rings, and collision of the plasma fluxes, should lead to substantially higher temperatures at an intermediate surface, equally distant from the two rings, than in the real case of two cylindrical beams with centers displaced from each other by a distance exceeding the transverse size of the beams u. Nevertheless, even in this case calculations showed that the x radiation, integrated over time, from the middle of the gap turned out to be 10% lower than at the centers of the region of energy dissipation. Thus, we have a further confirmation of the conclusion that there is no need of introducing, at least under our conditions, any anomalous heat conduction.

Experiments were carried out on the acceleration of thin targets of aluminum and polyethylene whose transverse dimensions were commensurate with the diameter of the focal spot. Comparison of interference patterns obtained in bombardment of such targets and targets with larger dimensions permitted estimation of edge effects, including energy loss along the target surface. In Fig. 6 we have shown the corresponding interference patterns (aluminum targets of diameter 300 μm and 5 mm were bombarded with identical laser-pulse parameters in an atmosphere of nitrogen).

A point of definite interest is the conical structure formed in the peripheral regions of the focal spot and extending significant distances from the target surface. A structure of this type is observed only in bombardment of targets with large transverse dimensions (see

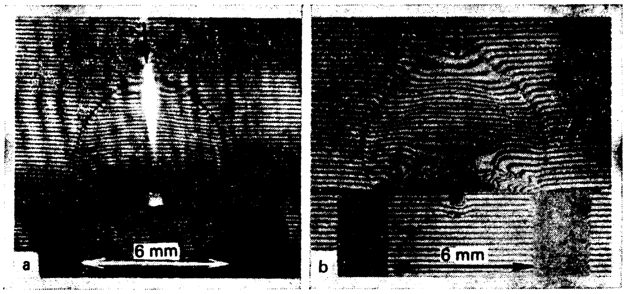

FIG. 6. Interference patterns obtained in bombardment of an aluminum foil of thickness 6 μm in a nitrogen atmosphere (p_0 = 5 mm Hg) and corresponding to a moment of time 23 nsec after the beginning of the bombardment. The exposure of the frames was 0.5 nsec. Frame a—diameter of bombarded target 300 μm, $E = 25J$, $\tau = 3.0$ nsec. Frame b—diameter of bombarded target 5 mm, $E = 25J$, $\tau = 3.0$ nsec.

Fig. 2). Its formation is apparently due to collision of the hot expanding plasma produced in the central regions of the focal spot with the cold plasma produced in the peripheral regions by the wings of the intensity distribution of the radiation at the target surface.

The absence of a conical structure in interference patterns obtained in bombardment of targets with small transverse dimensions confirms this idea. The difference in the apex angles of the cones for targets of different materials also fits into the idea of collision of the plasma fluxes. Also deserving attention is the dynamics of shock waves excited in the surrounding gas in experiments on bombardment of targets with small transverse dimensions. Analysis of the corresponding interference patterns may turn out to be useful for evaluation of the fraction of the laser-beam energy input into the accelerated portion of the target, and for study of the refraction of light beams in the plasma corona.

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