Mechanism of generation of hot electrons in a laser plasma

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Results are presented of an investigation of the interaction of high-power neodymium-laser pulses of 3.5 nsec duration with flat targets of various materials in the irradiance range 10^{12}–10^{14} W/cm^2. A correlation is established between the generation of the $(3/2)\omega_0$ harmonic and the appearance of the "hard" component in the x-ray spectrum. An analysis of the aggregate of the obtained data leads to the conclusion that the bulk of the electrons in the region $n_{cr}/4$ has a temperature corresponding to the "soft" component in the x-ray spectrum. The appearance of hot electrons was attributed to the development of two-plasmon parametric instability (the produced electron Langmuir waves are absorbed as a result of Čerenkov interaction with the electrons).

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Laser-plasma research has long ago indicated that hot superthermal electrons are generated under the influence of laser radiation in the plasma corona on the surface of an irradiated target (see, e.g., Ref. 1). What makes this fact important is that the energy of the laser pulse needed to perform a demonstration experiment on laser-mediated thermonuclear fusion, as well as the choice of the target construction, depends strongly on how strong a heating of the inner regions of the thermonuclear target can be expected as a result of penetration and absorption of the superthermal electrons and the hard x rays associated with them. The question of the origin of the hot electrons in the laser plasma therefore remains at the center of attention of physicists engaged in research on laser-mediated thermonuclear fusion. It must be emphasized that at the present time two mechanisms of generation of superthermal electrons are under discussion. One attributes the generation of the hot electrons to the Cerenkov mechanism of absorption, by the electrons, of the electron Langmuir plasma waves produced in the corona by the laser radiation (see, e.g., Ref. 2). The plasma waves can be excited both as a result of the development of decay parametric instabilities, and bilinear transformation of the incident electromagnetic wave near the region with critical density. A two-temperature electron distribution is then produced in one spatial region, which is the region where the plasma waves are generated. The other possibility is connected with the assumption that the electron heat transport is substantially decreased in comparison with the collisionless Knudsen transport and this is the cause of the possible overheating of that plasma-corona region in which substantial absorption of laser radiation takes place. It is then possible to state that the hot electrons are localized in a high-temperature region (the superheat region), while the cold electrons are localized in another lower-temperature region outside the superheat region. This premise is widely used in various theoretical models for the interpretation of the experimental data (see, e.g., Ref. 3).

The foregoing possible mechanisms of generation of hot electrons are usually regarded in the scientific literature on laser plasma as coexisting. This is due to the fact that up to now it was not assumed that the simultaneously measured experimental data on the plasma corona call for an analysis that could identify the real manifestation of one mechanism of generation of hot electrons or the other. We report here the first such analysis of the experimental data, which leads to the conclusion that under the conditions discussed below only one mechanism of generation of superthermal electrons is realized. Without making the approach general, we formulate our analysis using as an example experimental results obtained in the investigation of the interaction of laser radiation with a plasma corona under the conditions of the "Mishen'-1" facility.[4-7]

To arrive at the necessary conclusions concerning the role of different processes responsible for the production of fast electrons, we consider and discuss results of experiments on the irradiation of flat massive targets of different materials by nanosecond pulses from neodymium laser at moderate irradiances not exceeding $(2-3)\times 10^{14}$ W/cm^2 in the "Mishen'-1" facility.[4] It is perfectly clear that under other conditions, for example at higher irradiances or in experiments on spherical targets, a similar analysis can lead to substantially different mechanisms, one or several, responsible for the generation of the hot electrons.

A light beam with energy up to 50 J in a pulse of 3.5 nsec duration was focused by a lens with relative aperture 1 : 3.5 on surfaces of flat polyethylene, aluminum, copper, tin, and lead targets placed in a vacuum chamber. The laser beam divergence was 5×10^{-4} rad; the energy contrast was monitored in each experiment and was not less than 10^5. The measurements were made at different angles of beam incidence on the target (from 0 to 70°).

The plasma x-ray spectrum was investigated by the standard absorber method using a specially developed 12-channel system,[5] based on small-size CsI(Tl) crystal scintillation counters that ensured practically complete absorption of the radiation with quantum energy 100 keV. The radiation spectral interval registered by each channel was determined by the thickness of the aluminum foil placed ahead of the scintillator. The photomultiplier signals were registered with a multichannel memory unit made up of capacitive memory cells. The lower limit of registration of the radiation passing through the absorbing filters was $\sim 10^{-11}$ J/cm^2. Simultaneously with the x-ray measurements, we registered the plasma radiation at the frequencies ω_0, $2\omega_0$, and $(\frac{3}{2})\omega_0$ (ω_0 is the laser operating frequency). At normal incidence of the laser beam, we investigated the intensities and the spectral distributions of the radiation at the fundamental frequency and at the frequencies $2\omega_0$ and $(\frac{3}{2})\omega_0$, scattered into the aperture of the focusing lens. In the case of oblique incidence of the beam on the target, the observations were made in three directions: backwards into the aperture of the focusing lens, in the direction of the mirror reflection, and in the direction normal to the surface of the target. In addition, in a number of experiments, a time recorder operating in the slit-scanning regime (resolution time $\leq 5 \times 10^{-11}$ sec) was used to investigate the time variation of the intensity of the incident radiation and of the radiation scattered into the aperture of the focusing lens at the frequencies ω_0, $2\omega_0$ and $(\frac{3}{2})\omega_0$. The same instrument, in conjunction with a diffraction spectrograph, was used to obtain the time scan of the spectrum of the $(\frac{3}{2})\omega_0$ harmonic.[6]

An analysis of the entire aggregate of the data made it possible to establish a correlation between the generation of the $(\frac{3}{2})\omega_0$ harmonic and the appearance of the "hard" component in the x-ray spectrum.[7]

Figure 1 shows the x-ray spectra in the quantum energy range from 5 to 20 keV, obtained for normal incidence of the laser beam on the target from different materials. The irradiance in the focal spot on the target surfaces was 8×10^{13} W/cm^2. It is seen that in all cases the spectrum has a two-component structure. Assuming that the distribution function of the electrons in the plasma consists of two Maxwellian components with different temperatures, computer calculations made it possible to choose three parameters (the "cold" electron temperature T_0, the "hot" electron temperature T_1, and the relative number ξ of the particles in the hot component) for the corresponding experimental

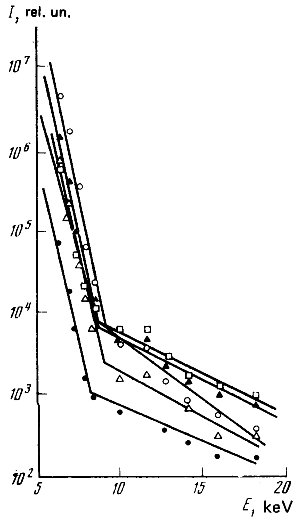

FIG. 1. X-ray spectra of plasma produced by irradiating targets of different materials: ●—$(CH_2)_n$, △—Al, ○—Cu, ▲—Sn, □—Pb.

TABLE I.

Material	T_0, eV	T_1, keV	ξ
$(CH_2)_n$	525±25	3.9±0.1	$3\cdot 10^{-6}$
Al	500±25	3.5±0.1	$1\cdot 10^{-5}$
Cu	450±25	2.7±0.1	$8\cdot 10^{-6}$
Sn	275±25	3.3±0.1	$3\cdot 10^{-6}$
Pb	300±25	3.6±0.1	$9\cdot 10^{-6}$

data. The results of such a reduction of the data of Fig. 1 are contained in Table I.

Figure 2 shows the x-ray spectra obtained at different angles of beam incidence on a polyethylene target. The results of the corresponding reduction are contained in Table II. The irradiance for all angles was 8×10^{13} W/cm^2.

In those cases when the x-ray spectrum contained no "hard" component, in our case at relatively small irradiance [$(1-2) \times 10^{13}$ W/cm^2] at normal incidence of the beam on the target, and at high irradiance ($\sim 10^{14}$ W/cm^2) for incidence angles 50–60°, it was impossible to register the $(\frac{3}{2})\omega_0$ harmonic in any of the three observation directions indicated above, even when the sensitivity of the measuring apparatus was increased by one order of magnitude. We note that up to incidence angles of 50–60° the reflection is specular for all the observed targets, and the corresponding directivity patterns are narrow and change relatively little on going from smaller to larger incidence angles. The observed specular character of the reflection is evidence that it comes from a sufficiently flat plasma layers in agreement with hydrodynamic calculations performed for conditions close to those of the here-described experiments. Sufficiently convincing proof of the described reflection picture is the vanishing of the radiation of the $2\omega_0$ harmonic at laser beam incidence on the target $\geq 20°$. (At the same time, as seen from Fig. 2, the "hard" component of the x-ray spectrum vanishes only at incidence angles larger than 50°). The small changes of the electron temperature with changing incidence angle allow us to conclude that in our conditions the main contribution to the plasma heating is made by the classical collision absorption mechanism in the plasma-

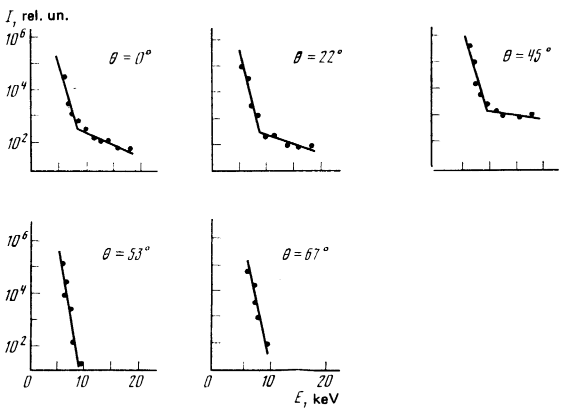

FIG. 2. Dependences of the intensity of the x rays passing through aluminum filters of various thickness on the incidence angles of the laser beam on the target (target—polyethylene, irradiance on the target surface $I = 8 \times 10^{13}$ W/cm^2).

TABLE II.

θ, deg	T_0, eV	T_1, keV	ξ
0	525	3.7	$6\cdot10^{-5}$
22	500	5.8	$2\cdot10^{-6}$
45	500	5.3	$2\cdot10^{-6}$
53	425	–	–
67	450	–	–

corona regions with densities less than critical.

We have subsequently focused our attention in our analysis of the hot-electron generation mechanisms on regions with density close to one-quarter of the critical value. The experimental data that are of importance for further analysis are those on the shape and width of the lines of the $(\frac{3}{2})\omega_0$ harmonic.

Figure 3 shows a typical time-integrated contour of the $(\frac{3}{2})\omega_0$ line, registered at normal incidence of the laser beam on an aluminum target (irradiance 8×10^{13} W/cm^2).

A similar two-component contour of the $(\frac{3}{2})\omega_0$ line is observed also when polyethylene targets are irradiated at small beam incidence angles. The distance between the maxima of the intensity, shifted relative to the position corresponding to the exact value $(\frac{3}{2})\omega_0$, is 40–50 Å in the wavelength scale. If we calculate, in accordance with Ref. 9, the electron temperature of the plasma from the distance between two maxima in the spectrum of the $(\frac{3}{2})\omega_0$ harmonic, then it turns out that the value obtained for all cases is quite close to the temperature of the "cold" electron component determined from the x-ray spectrum.

Figure 4 shows a typical streak photograph of the spectrum of the $(\frac{3}{2})\omega_0$ harmonic for an aluminum target at an irradiance 8×10^{13} W/cm^2. An appreciable redistribution of the energy in the spectrum takes place during the laser pulse, the relative intensities of the "red" and "blue" components change, and sometimes only one of the components is observed. Nonetheless, at all instants of time, the width of the spectral distributions of the intensity near $(\frac{3}{2})\omega_0$ does not exceed 80–100 Å.

In accordance with Ref. 8, it can be assumed that at sufficient excess above the threshold of the two-plasma parametric instability as a result of the turbulent broadening of the plasma-wave spectrum, the spectral line shape of the $(\frac{3}{2})\omega_0$ harmonic may or may not have

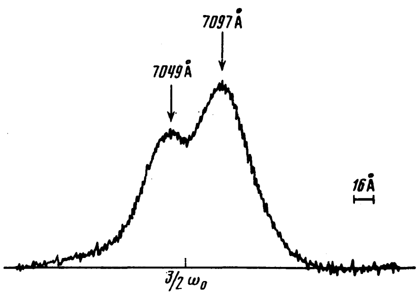

FIG. 3. Density pattern of spectral distribution of the $(3/2)\omega_0$ harmonic radiation (aluminum target, $I=8\times19^{13}$ W/cm^2).

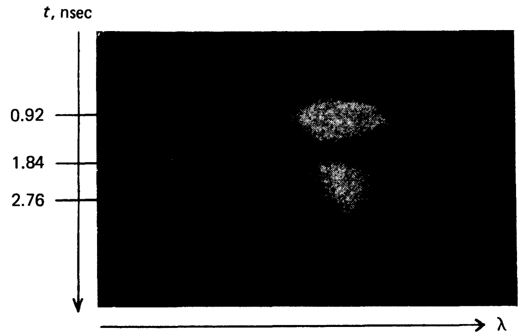

FIG. 4. Streak photograph of $(3/2)\omega_0$ harmonic (aluminum target, $I=8\times10^{13}$ W/cm^2).

a "double-hump" structure, and the line width can exceed the value determined by the temperature distance between two maxima. This means that the plasma electron temperature determined from the experimental data by comparing the widths of spectral distributions near $(\frac{3}{2})\omega_0$ with the theoretically estimated distance between two maxima can only be higher than the true value. However, and this must be emphasized, our data on the emission spectrum near the $(\frac{3}{2})\omega_0$ harmonic lead to an electron temperature that does not exceed the temperature T_0 of the cold electrons. It can thus be stated that in a region with density close to one-quarter the critical value, from which the $(\frac{3}{2})\omega_0$ harmonic is radiated, the temperature of the bulk of the electrons is much less than T_1 and is close to T_0. By the same token, we establish the absence of plasma superheating (to the temperature T_1) in the region with densities close to $n_{cr}/4$. We note here that the presence of a small number of hot electrons does not manifest itself in the emission spectrum of the $(\frac{3}{2})\omega_0$ harmonic.

Ruling out the possibility of superheating the plasma in the $(\frac{3}{2})\omega_0$ generation region, we now use the experimentally established fact that a correlation exists between the generation of this harmonic and the generation of the "hard" component of the x-rays. This correla-

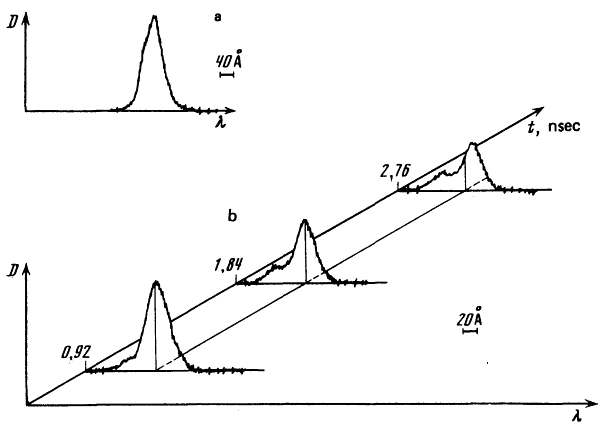

FIG. 5. Time scan of $(3/2)\omega_0$ harmonic radiation with high spectral resolution: a—time-integrated contour of the $(3/2)\omega_0$ harmonic (shown for comparison); b—density patterns corresponding to different instants of time shown in Fig. 4.

tion allows us to assume that both phenomena are realized in one spatial region and are due to a single cause, the two-plasma parametric instability that sets in when the threshold flux is exceeded.[9] Accordingly, the electron Langmuir waves of frequency $\omega_0/2$ generated in the plasma, first, produce the $(\frac{3}{2})\omega_0$ harmonic by combining with the laser radiation and, second, lead to generation of the hot electrons when absorbed as a result of the Cerenkov interaction with the electrons. All this allows us to state that under the conditions of experiment with the "Mishen'-1" facility the hot electrons are generated in a region with densities close to one-quarter the critical density, not as a result of the superheating of the plasma but because of the Cerenkov acceleration of the electrons by the electron Langmuir waves, which are the products of two-plasmon parametric instability. It seems to us that the approach described in the present communication is quite general and is of particular interest under conditions of interaction between the plasma corona and the CO_2-laser radiation, where the problem of anomalous heat transport is still quite vital because of the low densities in the absorption band.

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Dynamics of the modulational instability of a broad spectrum of Langmuir waves

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We consider the modulational instability of a Langmuir turbulence spectrum in which the group velocities of the waves are large compared to the ion sound speed. We obtain a dispersion relation which enables us to determine the threshold and growth rate of the instability for an arbitrary ratio of the spatial scale of the modulation to the characteristic wavelength of the Langmuir oscillations. We derive and solve by the inverse scattering method an equation which describes the nonlinear stage of the instability of one-dimensional long-wavelength perturbations at small excess above threshold. We establish that the transition of the instability into the nonlinear regime is qualitatively similar to the hard excitation of turbulence in hydrodynamics.

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1. INTRODUCTION

The present paper is devoted to the non-linear stage of the one-dimensional modulational instability of a spectrum of Langmuir waves with random phases.[1,2] The special feature of the one-dimensional problem is that here the possibility of Langmuir collapse is excluded, i.e., non-linear effects necessarily lead to a stabilization of the growth of the modulational perturbations (see Ref. 3). Depending on how the amplitude of the non-linear oscillations behaves in the transition through the instability threshold, one can distinguish between two stabilization regimes: soft and hard. In the first case the amplitude just above threshold turns out to be small, and in the second case it reaches a finite magnitude at arbitrarily small excess above threshold. The problem of which of these two regimes is realized in the case of the modulational instability was not clear until recently. The present paper contains an answer to that question: if the instability threshold corresponds to long-wavelength perturbations, the regime is hard. This conclusion is based upon results given in section 3, where we obtain and solve a non-linear equation which describes the evolu-

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