Local temperature of a plasma corona

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The temperature of a laser plasma is usually determined from its x-ray emission. The electron temperature T_e found by this method, however, is an average over space and time, while we are more interested in the local value of this temperature in the absorption zone. Avrov *et al.*[1] suggested determining the temperature from the distance between the "red" and "violet" satellites of the (3/2) ω_0 harmonic. The arguments advanced in Ref. 1, however, apply only just above the threshold for the instability involving the decay of the incident electromagnetic wave into two plasma waves (the $2\omega_{pe}$ instability). In the present letter we show that the electron temperature in the absorption zone can be determined over a broad range of laser beam intensities by measuring the temporal profile of the emission at the (3/2) ω_0 harmonic.

The present experiments were carried out in the MIShEN' 1 device.[2] The beam from a neodymium laser ($\tau_{\text{pulse}} = 3.5$ ns, energy up to 50 J) was focused onto the surfaces of plane disks in a vacuum chamber by a lens with an aperture ratio of 1:3.5 (the focus diameter did not exceed 100 μm). The energy contrast of the laser pulse was 10^4. Bulk plane disks of polyethylene $[(CH_2)_n]$, aluminum, copper, and lead were bombarded in experiments in which the disk surfaces made various angles with the laser beam. In each experiment we measured the energy and shape of the laser pulse, the far-zone distribution of the laser beam intensity, the intensities of the reflected and scattered light at the working frequency of the laser (ω_0), the x-ray emission spectrum of the plasma over the energy range 5–30 keV, and the intensity of the plasma emission at the frequencies $2\omega_0$, $(3/2)\omega_0$, and ω_0 (these measurements of the plasma emission intensity were time-resolved, with a resolution $\leqslant 5\times 10^{-11}$ s) (Ref. 3). The measurements were carried out at laser beam power densities in the range 10^{13}–10^{14} W/cm^2. Detailed studies[4] have shown that at the focus sizes in these experiments the expansion of the plasma in the region with densities between $n_{\text{solid-state}}$ to $n_{\text{crit}}/4$ can be assumed uniform. Taking this approach, we carried out a series of numerical calculations based on the one-dimensional, two-temperature hydrodynamic model with bremsstrahlung, anomalous absorption, the electron thermal conductivity (with a limitation on the radiative loss rate), and energy exchange between electrons and ions. These calculations were carried out for the present experimental conditions (for the particular time evolution of the laser pulse) over the power-density range 10^{13}–10^{14} W/cm^2. We calculated the time evolution of the intensity of the emission at the $(3/2)\omega_0$ harmonic. This emission results from the coalescence of the incident light (ω_0) with a plasma wave

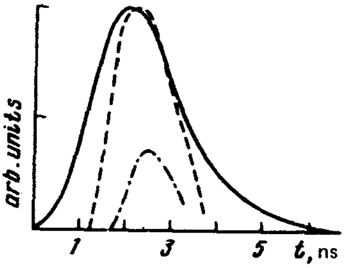

FIG. 1. The laser pulse (solid curve) and the plasma emission pulses at the frequency $(3/2)\omega_0(\lambda = 1.06\ \mu m)$. Dashed curve—$I = 10^{14}$ W/cm^2; dot-dashed curve—$I = 10^{13}$ W/cm^2. These are the results of numerical calculations.

$\omega_{pe} \simeq \omega_0/2$, which results from a 2 ω_{pe} instability. The anomalous absorption due to this instability is taken into account by means of an effective collision rate $v_{\rm eff} = \alpha\omega_{pe}(v_T/c)^2$, where ω_{pe} is the plasma frequency, v_T is the electron thermal velocity, c is the speed of light, and α is a coefficient on the order of unity.

Figure 1 shows the dependence $I_{(3/2)\omega}(t)$ obtained from these calculations (the intensity was calculated in accordance with Refs. 5 and 6). Figure 2 shows the synchronized laser pulse and the emission pulse at $(3/2)\omega_0$. We see that the calculated and experimental curves agree quite well. The $(3/2)\omega_0$ emission pulse is noticeably delayed with respect to the beginning of the bombardment. It reaches a maximum after a delay with respect to the maximum of the laser pulse; the harmonic generation does not disappear until the intensity is lowered to a level significantly below that at which it appears.

Under our experimental conditions the threshold for the $2\omega_{pe}$ instability is determined by collisions. This conclusion is implied by the observed increase in the threshold for this instability with increasing Z of the target material ($I_{\rm thr} = 8\times 10^{12}$ W/cm^2

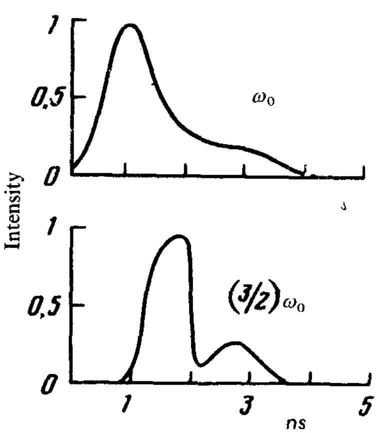

FIG. 2. Time evolution of the pump laser pulse (ω_0) and of the emission pulse at the $(3/2)\omega_0$ harmonic. (Aluminum target, $I = 1\times 10^{14}$ W/cm^2).

TABLE I.

Material	Laser beam intensity	$T_{e\text{-on}}$	$T_{e\text{-off}}$	$T_{e\text{-x}}$
	10^{14} W/cm^2	0.8 keV	1.2 keV	0.5 keV

for polyethylene, $I_{\text{thr}} = 2\times 10^{13}$ for aluminum, and $I_{\text{thr}} > 10^{14}$ for lead) and by the simultaneous decrease in the temperature[1] ($T_e = 0.5$ keV for the polyethylene and $T_e \simeq 0.3$ keV for the lead). At the time at which the $(3/2)\omega_0$ harmonic appears and disappears, therefore, the condition $\gamma = \sqrt{3}/8\omega_{pe}(I_0/m_e nc^3)^{1/2} = \nu_{ei}/2$ should hold (m_e is the electron mass, n is the plasma density, I_0 is the laser beam intensity, and ν_{ei} is the rate of electron-ion collisions). The temperature can be determined from this condition. The temperatures found in this manner are shown along with the temperatures found from the x-ray emission in Table I [$T_{e\text{-on}}$ is the temperature corresponding to the appearance of the $(3/2)\omega_0$ harmonic; $T_{e\text{-off}}$ is the temperature corresponding to the disappearance of the $(3/2)\omega_0$ harmonic; and $T_{e\text{-x}}$ is the temperature determined from the x-ray emission].

We see that the temperature when the harmonic is "turned off" is 1.5 times that when the harmonic is "turned on." This effect can be attributed to a heating of the plasma during the pulse. The plasma temperature in the $n_{\text{crit}}/4$ region is higher than the average value found from the x-ray emission, implying a local relative heating of the plasma in this region. The numerical calculations lead to a corresponding result.

We might note that the temperatures given in Table I near $n_{\text{crit}}/4$ agree with an estimate found from the measured width of the $(3/2)\omega_0$ line.[6]

It follows from Figs. 1 and 2 that the intensity of the $(3/2)\omega_0$ harmonic increases sharply with increasing laser beam intensity. A corresponding behavior was observed in Refs. 2 and 7 for pulses in the nanosecond and picosecond ranges. A qualitative explanation for the observed behavior runs as follows: The intensity of the $(3/2)\omega_0$ harmonic depends strongly on the temperature, and under these particular experimental conditions, with a relatively modest absorption near $n_{\text{crit}}/4$, the intensity is determined by[5,6]

$$I_{(3/2)\omega} \sim I_0 (v_T/c)^5 (m_e/M)^{1/2} (\omega_{pe} L/c)(I_0/m_e nc^3)^{-1/3},$$

where M is the ion mass, and L is the scale dimension of the density gradient.

If we assume that the heat flux is proportional to nTv_T, and if we use $v_{\text{eff}}L/c$ as the fraction of the radiation absorbed near $n_{\text{crit}}/4$, we find $I_{(3/2)\omega} \sim I_0^{17/3}$. The increase in $I_{(3/2)\omega_0}$ continues up to intensities at which ponderomotive forces cause a significant deformation of the density profile in the absorbing layer.

In summary, analysis of the time evolution of the emission at the $(3/2)\omega_0$ harmonic yields important information about the local plasma temperature in the $n_{\text{crit}}/4$ region.

1)The question of the Z dependence of the temperature apparently cannot be resolved unambiguously. Contributing factors are the pulse shape, the bombardment geometry, etc. The average temperature found from the x-ray emission in our experiments fell off with increasing Z.

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