# Investigation of the reflection of laser radiation from a dense plasma

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The paper presents the results of an experimental investigation of the reflection of laser radiation from a plasma produced by focusing plane-polarized neodymium laser radiation ($\lambda = 1.06\mu$) of flux density ranging from $5\times10^{10}$ to $5\times10^{12}$ W/cm² on the surfaces of targets with different atomic numbers. The reflection coefficient is observed to decrease anomalously rapidly, starting from flux densities $\sim10^{12}$ W/cm². The spectrum of the radiation reflected back into the solid angle of the focusing lens contains a line of wavelength $\lambda = 0.53\ \mu$, which corresponds to the second harmonic of the radiation incident on the target. A ruby laser ($\lambda = 0.69\mu$) synchronized with the neodymium laser, and with its probing radiation focused on the same focal spot, was used to measure the reflection coefficient at another wavelength. The results are discussed.

## INTRODUCTION

The study of the processes of radiation reflection from a plasma is of great interest in connection with the problem of plasma heating to thermonuclear temperatures by laser radiation[1,2]. It should be noted that light reflection by a plasma is a parasitic phenomenon, since it decreases the energy input into the plasma, and leads to the destruction of the active elements of the laser system. On the other hand, investigation of the radiation reflected by the plasma allows us to determine the set of parameters of the disintegrating plasma, to draw conclusions about the absorption mechanisms, etc.

Despite the large number of already existing experimental papers devoted to the investigation of the reflection from plasmas of nanosecond laser radiation pulses, there does not exist a unique picture of how the reflection coefficient depends on the flux density, of how it evolves during the laser pulse, etc. The difference in the values of the reflection coefficient obtained under roughly identical conditions attains in different experiments two-three orders of magnitude (e.g.,[3-14]) (see Fig. 1, as well as[15]).

In the present paper we carry out an experimental investigation of radiation of flux densities ranging from $5\times10^{10}$ to $5\times10^{12}$ W/cm² reflected from a target.

## SCHEME OF THE EXPERIMENTAL SETUP AND THE EXPERIMENTAL RESULTS

The scheme of the experimental setup is shown in Fig. 2. Neodymium laser radiation pulses of duration ~ 4 nsec at the half-power level and leading-edge width ~ 1.5 nsec were focused by a lens of focal length f = 5 cm on the surface of a target located in a vacuum chamber. The contrast of the radiation was not worse than $10^{-4}$. The diameter of the laser beam on the focusing lens was equal to 1.5 cm, and the maximum angle of incidence $\theta_{max}$ of the radiation on the surface of a plane target was 9°. The energy of the radiation incident on the target was varied at constant laser energy within a wide range of values with the aid of calibrated central light filters which did not change the space-time parameters of the radiation. In this case the maximum flux density at the target reached $5\times10^{12}$ W/cm² at the focal spot, which had a diameter of 60 $\mu$.

As targets we used solid Be, Al, Cu, Zn, Ta, and Pb samples, as well as aluminum and polyethylene $(CH_2)_n$ foils of different thicknesses[16]. The incident, reflected, and transmitted (through the target) radiation beams were led off by parallel plates to calorimeters and FÉK-09 and FÉK-15 coaxial photocells. The signals from the coaxial photocells were recorded on a 6-LOR-02 six-beam oscillograph. The time resolution of the recording system was not worse than ~ $10^{-9}$ sec.

Figure 3 shows the dependence of the coefficient of reflection (in terms of energy) of the radiation into the solid angle of the lens on the density of the radiation flux incident on the aluminum target. Figure 4a shows a characteristic oscillogram of the incident and reflected light pulses for a flux density of $5\times10^{12}$ W/cm², while Fig. 4b shows the behavior of the reflection coefficient during the laser pulse.

In Fig. 5 we show the dependence of the integrated (over a pulse) reflection coefficient on the atomic number of the target. The reflection coefficient decreases by roughly a factor of two as the atomic number is increased.

To investigate the reflection coefficient of the plasma during a heating pulse at another wavelength, we used a ruby laser ($\lambda$ = 0.69 $\mu$), whose radiation was led with the aid of a system of prisms and mirrors to the axis of the focusing system and focused on the surface of the target at the same focal spot, the angular misalignment of the neodymium and ruby laser beams not exceeding

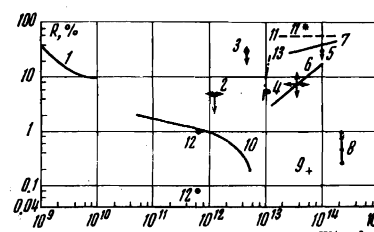


FIG. 1. A review graph of the results of the experimental investigations of the coefficient of reflection from a plasma of nanosceond laser radiation pulses of different flux densities. The numbers on the graph denote the references: 1–[3], 2–[11], 3–[9], 4–[7], 5–[8], 6–[10], 7–[4], 8–[6], 9–[5], 10–present work, 11–[12], 12–[13], and 13–[14].

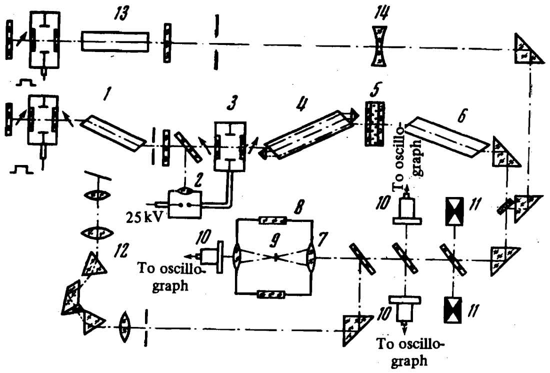


FIG. 2. Diagram of the experimental setup: 1) neodymium laser with a Q-switching Kerr cell, 2) laser-actuated discharge gap, 3) shaping Kerr shutter, 4) three-pass first amplifier, 5) vessel with a bleachable dye, 6) second amplifier, 7) focusing lens, 8) vacuum chamber, 9) target, 10) coaxial photocells, 11) calorimeters, 12) prism spectrograph, 13) ruby laser with a Q-switching Kerr cell, 14) diverging lens compensating for the chromatic aberration of the focusing lens.

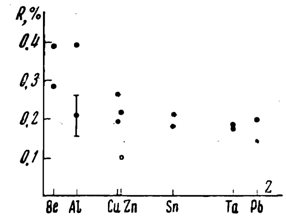


FIG. 5

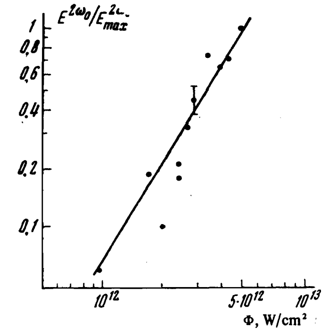


FIG. 6

FIG. 5. The experimental dependence of the integrated (over the pulse duration) reflection coefficient on the atomic number of the target for $\Phi = 5 \times 10^{12}$ W/cm².

FIG. 6. The experimental dependence of the energy radiated by the plasma into the solid angle of the lens at $\lambda = 0.53\mu$ on the flux density $\Phi$. As the energy unit we took $\sim 5 \times 10^{-6} - 5 \times 10^{-5}$ times the maximum laser energy.

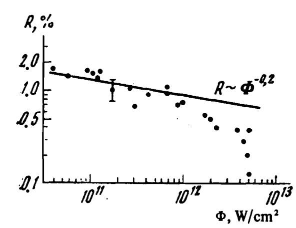


FIG. 3

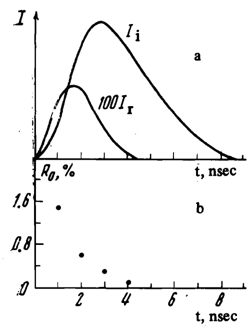


FIG. 4

FIG. 3. The experimental dependence of the integrated (over the pulse duration) coefficient $R = E_r/E_i$ of reflection of the radiation into the solid angle of the lens on the flux density $\Phi = W/St_0$ for the aluminum target (W is the laser energy, $t_0$ is the pulse width, and S is the area of the focal spot).

FIG. 4. The time dependence for $\Phi = 5 \times 10^{12}$ W/cm² of: a) the incident and reflected pulses; b) the instantaneous reflection coefficient $R_0$.

$10^{-4}$ rad. To compensate for the chromatic aberration of the focusing lens, and equalize the sizes of the focal spots, a diverging lens and diaphragms were mounted in the path of the ruby laser beam.

The ruby laser was synchronized with the neodymium laser, so that the neodymium laser radiation pulse fell on the maximum of the probing ruby laser pulse. The flux density of the probing ruby laser radiation at the target was $< 5 \times 10^9$ W/cm², and the ratio of the flux density of the probing signal to that of the heating signal was less than $10^{-3}$. The ruby laser radiation pulses incident on, and reflected by, the plasma were also led off by parallel plates to coaxial photocells (not shown in diagram of the experimental setup), the signals from which were recorded on 6-LOR-02 and I-2-7 oscillographs.

The spectral composition of the radiation reflected into the solid angle of the focusing lens was investigated in the visible region with the aid of a prism spectrograph. Starting from flux densities $\sim 5 \times 10^{11}$ W/cm², for all the targets used in the experiment, the spectrum of the backward reflected radiation contained a $\lambda = 0.53$-$\mu$ line, corresponding to the second harmonic of the $\lambda = 1.06$-$\mu$ incident radiation [17]. The halfwidth of the $\lambda = 0.53$-$\mu$ line was $\sim 10$ Å. The line width of the incident radiation was measured with the aid of a Fabry-Perot interferometer, and had roughly the same value.

Figure 6 shows the dependence on the radiation flux density $\Phi$ incident on the target of the total energy radiated during a laser burst by the plasma at wavelength $\lambda = 0.53\ \mu$.

## DISCUSSION OF THE RESULTS

### A. Determination of the Electron Density Gradient

During the interaction of a high-power laser radiation with matter there is formed in times $< 10^{-10}$ sec a high-temperature plasma with a density profile dropping from the density of the solid $N_e \sim 10^{23}$ cm$^{-3}$ to zero. There is in this profile a point at which the plasma frequency $\omega_{Le} = (4\pi e^2 N_e/m)^{1/2}$ is equal to the frequency $\omega_0$ of the heating radiation ($\omega_{Le} \gg \nu_{ei}$, where $\nu_{ei}$ is the electron-ion collision rate). At the neodymium laser frequency $\omega_0 = 1.8 \times 10^{15}$ sec$^{-1}$, the permittivity $\epsilon$ vanishes at the density $N_e = 10^{21}$ cm$^{-3}$, and there is effective reflection of the incident radiation in the vicinity of this point. The absorption of the radiation from the point $x = 0$ to some point $x = a$ is determined by the bremsstrahlung absorption coefficient K for the plasma given by the expression [18]

$$K = \omega_{Le}^2 / c\omega_0\tau(\omega_0^2 - \omega_{Le}^2)^{1/2},$$

where $\tau = 2.4 \times 10^4 T_e^{3/2}/N_e Z$ is the electron-ion collision time, Z is the ion charge, and $T_e$ is the electron temperature in electron volts. The overall absorption coefficient has the form

$$K_t = 2\int_0^a K\,dx, \qquad (1)$$

where the factor 2 in front of the integral takes account of the double passage of the radiation through the layer.

The density profile in the laser plasma can be assumed to be linear for densities $\sim 3 \times 10^{20} - 10^{21}$ cm$^{-3}$, i.e., in the narrow region where there is effective absorption. Then substituting into the integral (1)

$$\omega_{Le}^2(x) = 4\pi N_e(x) e^2/m = x\omega_0^2/a$$

and $\tau(x) = \tau(a)N_e(a)/N_e(x)$, and integrating, we obtain for the reflection coefficient

$$\ln R = -{}^{32}/_{15}a/c\tau(a). \quad (2)$$

A similar result can be arrived at on the basis of the equation[19].

Thus, knowing the reflection coefficient, we can determine from the formula (2) the value of the characteristic size of the inhomogeneities

$$a = \left(\frac{1}{N_e}\frac{dN_e}{dx}\right)^{-1}$$

or of the electron density gradient $dN_e/dx$ in the region close to the critical point, under the assumption that the temperature remains constant over the pulse duration[11,20] and along the absorption region.

The variation of the characteristic dimension of an inhomogeneity during a laser pulse for a flux density of $5 \times 10^{12}$ W/cm$^2$ is shown in Fig. 7. (The value $T_e$ = 330 eV of the temperature for this flux density was taken from[21], and the degree of ionization was calculated by an approximate method[22]). It should be noted that it is apparently not possible to measure the electron density gradient near the critical density by other methods. For example, the measurement of the gas-dynamical laser-flare parameters by the interferometric method did not allow the investigation of the region with densities above $5 \times 10^{19}$ cm$^{-3}$, owing to the strong absorption and refraction of the probing radiation near the target surface[23].

Of great interest is the determination of the electron density gradient for $N_e > 10^{21}$ cm$^{-3}$, i.e., in the regions where the heating radiation does not penetrate. With that end in view, to probe the plasma, we used a ruby laser ($\lambda = 0.69\ \mu$), for whose radiation the critical density has the value $N_e = 2.4 \times 10^{21}$ cm$^{-3}$. The coefficient of reflection of the ruby-laser radiation was $\sim 1\%$ during the third nanosecond of the heating pulse, and decreased toward the end of the pulse, the reflection parameters for the $\lambda = 1.06$-$\mu$ signal being unaffected by the presence of the probing radiation.

Again using (2), we obtain for a flux density of $5 \times 10^{12}$ W/cm$^2$ and at the point $N_e = 2.4 \times 10^{21}$ cm$^{-3}$ an electron density gradient equal to $dN_e/dx \approx 9 \times 10^{24}$ cm$^{-4}$ (during the third nanosecond), i.e., $dN_e/dx$ increases sharply (by roughly a factor of 7–8) at densities above $10^{21}$ cm$^{-3}$. It should, however, be noted that the above estimates for the electron density gradients make sense only in the case when the bremsstrahlung mechanism plays the dominant role in the absorption of the laser radiation by the plasma.

### B. Anomalous Absorption and the Generation of the Second Harmonic

Let us now consider the experimental dependence of the coefficient of reflection of the laser radiation on the flux density $\Phi$ (Fig. 3). As the flux density varies from $\sim 3 \times 10^{10}$ to $7 \times 10^{11}$ W/cm$^2$, the reflection coefficient decreases according to the law $R \sim \Phi^{-0.2}$. Starting from flux densities $\sim 7 \times 10^{11}$ W/cm$^2$, the reflection coefficient begins to fall anomalously rapidly, and there appears in the spectrum of the reflected signal a $\lambda = 0.53$-$\mu$ line whose intensity increases rapidly with energy. The cause of such an anomalously strong absorption could be the development in the plasma of parametric instability[24].

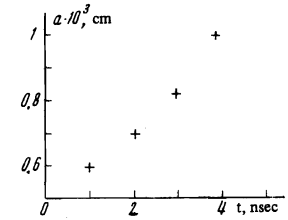


FIG. 7. The behavior of the characteristic plasma dimension $a = N_e(dN_e/dx)^{-1}$ for $N_e = 10^{21}$ cm$^{-3}$ and $\Phi = 5 \times 10^{12}$ W/cm$^2$ during the laser pulse (under the assumption that the temperature remains constant at $T_e$ = 330 eV).

The threshold value of the electric-field strength for the decay of the transverse light wave into longitudinal electron Langmuir ($l$) and ion-acoustic (s) oscillations ($t \to l + s$) for $\omega_0 = \omega_{Le}$ is given by the expression[25]

$$E_{\text{thr}}^2 = 4(2\pi)^{3/2}\frac{\omega_{Li}}{\omega_{Le}}\frac{\nu_{ei}}{\omega_0}N_e\varkappa T_e,$$

when $N_e = 10^{21}$ cm$^{-3}$, for a hydrogen plasma $E_{\text{thr}} \approx 10^7/T_e^{1/4}$ V/cm, where $T_e$ is in keV. For $T_e \approx 250$ eV the threshold value of the flux density is $\Phi_{\text{thr}} \approx 10^{12}$ W/cm$^2$, which is in good agreement with the obtained experimental results.

The second harmonic can be generated as a result of the confluence $t + l \to t$, or $l + l \to t$.

Another mechanism which can give rise to an increase in the coefficient of absorption of light by a laser plasma is the phenomenon of linear transformation of a transverse wave of frequency close to the plasma frequency into an electron Langmuir oscillation[26]. However, both the linear-transformation coefficient[27] and the efficiency of generation of the second harmonic[28] strongly depend on the angle of incidence of the radiation on the plasma. The absorption coefficient has a narrow maximum at $\sin\theta = 0.5(a\omega_0/c)^{-1/3}$. For $a \approx 10^{-3}$ cm and $\omega_0 = 1.8 \times 10^{15}$ sec$^{-1}$, the optimum angle of incidence is $\theta \approx 10°$, which is roughly two times larger than the mean angle of incidence of the radiation on the target in our experiment.

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