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"TRANSPARENCY" EFFECT PRODUCED BY LASER PULSES IN A PLASMA

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The results of measurement of absorption of laser radiation in a plasma are presented. It is shown that for radiation fluxes of 10^2–10^3 MW/cm^2 the absorptivity of a xenon plasma is appreciably smaller than at low intensities. The effect can be explained by a rapid decrease of the population of the upper atomic levels due to ionization of the excited atoms by electrons and laser quanta under such conditions when excitation of the atoms from the ground state is a much slower process.

IN our previous article[1] we reported on the effect of a sudden increase in the absorptivity of a partially ionized gas at large light intensities. In a xenon plasma with a heavy-molecule density 6.5×10^{18} cm^{-3}, at a temperature of about 11 000°K, and a degree of ionization of about 0.15, the absorption increased strongly in comparison with the usual "linear" absorption. This was observed at light intensities J from a ruby laser which are approximately 10^{-2} times the threshold for the breakdown of cold xenon of the same density, namely $J_t \simeq 1.4 \times 10^5$ MW/cm^2, i.e., at $J > 10^3$ MW/cm^2.

Below we report on another effect—the decrease in absorptivity of the same plasma in comparison with the "linear" absorption of low-intensity light. This "transparency" effect of a plasma was observed in the range of not very large intensities: $J \simeq (10^{-3}$ to $10^{-2})J_t$, or $J \simeq (10^2$ to $10^3)$ MW/cm^2.

We investigated the absorption of light in a xenon plasma formed in a shock tube behind a reflected shock wave. As in [1], the calculated equilibrium temperature behind the front of the reflected wave was T = 11 000°K; the numbers of neutral atoms and electrons were $N_a = 5.5 \times 10^{18}$ cm^{-3} and $N_e = 0.97 \times 10^{18}$ cm^{-3}. The Q-switched ruby laser pulse of 50 nsec duration passed through windows in the pipe at a distance of 1 cm from the large-diameter end (the path was 8 cm). The light beam was slightly focused by a long-focus lens with f = 23 cm, and was almost parallel inside the tube. The pulses with a power of 20 MW were attenuated by means of neutral light filters.

The oscillogram of the transmission of the gas laser light with $\lambda = 6328$ Å through the plasma, close to $\lambda = 6943$ Å, showed that the "linear" absorption decreases in time with increasing distance from the front of the reflected shock wave to the viewing windows. This should be interpreted as the result of the gradual cooling of the stationary plasma due to radiation losses. In order that the light pass through the plasma with the same parameters in every one of the numerous experiments, the timing of giant pulses was carefully synchronized with the functioning of the shock tube. The laser operated at a definite time—100 μsec after the instant when the reflected wave passed by the windows. Judging from the oscillogram obtained with the gas laser, the plasma parameters in this instant did not differ strongly from those immediately behind the front.

In every experiment, we took oscillographs of the forms of the pulses incident on and transmitted through the plasma, which were almost similar (see Fig. 2, and also [1]), and the power ratio P_{tr}/P_{inc} was measured at the moment of the peak; in doing this the reflection from the window was automatically taken into account, so that P_{tr}/P_{inc} characterizes only the absorption. The results of this series of experiments, shown in Fig. 1, clearly exhibit the "transparency" picture. In Fig. 2, pertaining to a different series of experiments, the transparency effect is expressed more weakly, but on the other hand we here encompassed a wider range of intensities, including the effect of increased absorption.[1] Here, as in [1], the laser operated at the latest instant, approximately 300 μsec after the reflected wave passed by the window, when the temperature of the plasma, owing to radiative cooling, was appreciably less than the estimated temperature, and the "linear" absorption was considerably less than in the first series of experiments.

Let us turn to an explanation of the "transparency" effect. There are two main mechanisms for the absorption of light in a monatomic plasma: photoionization of excited atoms, and inverse bremsstrahlung absorption in the field of ions. We denote the corresponding absorption coefficients, corrected for stimulated emission by κ_{ph} and κ_{br}; $\kappa = \kappa_{ph} + \kappa_{br}$. As is known (see for example, [2]),

$$\varkappa_{ph} = \sum N_n \sigma_n (1 - e^{-h\nu/kT}), \quad \varkappa_T \sim N_e^2 T^{-1/2} (1 - e^{-h\nu/kT}),$$

where N_n is the density of atoms in the n-th level, σ_n

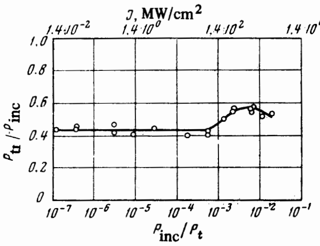

FIG. 1

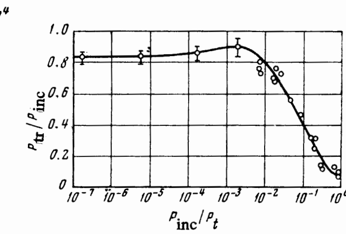

FIG. 2

FIG. 1. The dependence of the amount of laser radiation transmitted through partially ionized xenon on the intensity of light at T = 10^4 °K. P_t – threshold value of the power for the breakdown in cold xenon, equal to 20 MW.

FIG. 2. The same as in Fig. 1, but at T = 9×10^3 °K.

is the photoeffect cross section, and the sum goes over all levels taking part in the absorption of quanta $h\nu = 1.78$ eV.

As a result of the absorption of laser light, the electron gas warms up, and at sufficiently high intensities, say on the order of 10 eV, the excess of electron temperature over the initial value $T_0 \simeq 1$ eV becomes appreciable. It is easy to estimate that this arises precisely at those intensities at which the "transparency" begins to be visible. Under the conditions of complete thermodynamic equilibrium, the increase of temperature brings about a rise in absorption:

$$\varkappa \sim N_a T e^{-(I-h\nu)/kT}(1 - e^{-h\nu/kT})$$

(I—ionization potential).

However, under conditions of short laser pulses, and not too much heating, the total number of electrons and excited atoms $N_e + N^*$ ($N^* = \Sigma N_n$) does not have time to change. Indeed, it is possible to estimate that the processes of excitation and ionization of atoms from the ground state at $T \simeq 1-1.5$ eV take a longer time. Meanwhile, the ionization of excited atoms by electron impact takes place quickly; equilibrium between N_n and N_e, which is regulated by the processes of ionization and recombination at the upper levels, is established in a time of $\sim 10^{-11}$ sec. As the temperature rises, the state of equilibrium is shifted to the side of ionization, and just this circumstance—the decrease in the number of absorbing ionized atoms—is the main cause of the transparency; the value of κ_{ph} is at first five times larger than κ_{br} [approximately, $\kappa_{ph}/\kappa_{br} = \exp(h\nu/kT) - 1$].

At the same time, such a shift decreases the number of electrons almost not at all, so that owing to the cutting out of the upper levels in the plasma $N^* \ll N_e$. Under the conditions of partial thermodynamic equilibrium (equilibrium between N_n, N_e, and T), when $N_n \simeq N_e^2$, we have the approximation

$$\varkappa \sim N_e^2 T^{-1/2}(e^{h\nu/kT} - 1).$$

We see that when N_e = const, κ decreases with increasing temperature.

There is still another cause for the decrease of κ_{ph} and κ, namely the loss of excited atoms, due to photoionization by the laser light. This additional process also decreases the quasistationary population of the upper levels, but cannot completely eliminate the excited atoms because of the existence of induced photorecombination. Estimates show that it begins to play a marked role (compared with the continually occurring ionization by electron impact), approximately at the same intensities of light at which the transparency is observed.

At sufficiently high radiation intensities, the heating of electrons turns out to be large, on the order of several electron volts, and during the time of the pulse the additional ionization of atoms that were excited earlier takes place, which leads in the last account to an increase of absorption, as is observed in [1] (see Fig. 2). A quantitative description of this picture and details of the experiments, which are continuing, will be given in subsequent publications.

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[1] N. A. Generalov, G. I. Kozlov, and Yu. P. Raĭzer, ZhETF Pis. Red. 8, 138 (1968) [JETP Lett. 8, 82 (1968)].
[2] Ya. B. Zel'dovich and Yu. P. Raĭzer, Fizika udarnykh voln i vysokotemperaturnykh gidrodinamicheskikh yavleniy (Physics of Shock Waves and High-temperature Hydrodynamic Phenomena), Nauka, 1966.

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