Experimental investigations of the mechanisms of excitation of plasma waves and generation of harmonics in a plasma produced by an intense laser pulse

V. V. Aleksandrov, S. I. Anisimov, M. V. Brenner, E. P. Velikhov, V. P. Vikharev, V. P. Zotov, N. G. Koval'skiĭ, M. I. Pergament, and A. I. Yaroslavskiĭ

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The interaction mechanism between laser radiation ($\lambda = 1.06\mu$) and a high-temperature plasma is investigated for light fluxes between 10^{12}W/cm^2 and 4×10^{14}W/cm^2. A comparison of the measurement results obtained by various methods indicates that at light fluxes exceeding $\sim10^{13}$W/cm^2, effective absorption of the radiation is due to the development of decay instabilities $t\rightarrow p+s$ and $t\rightarrow p+p$. It is found that radiation of frequency $(3/2)\omega_0$ emitted by the plasma is due to Raman scattering by the plasma waves with frequencies close to $\omega_0/2$. The experimental values of the threshold light fluxed obtained with targets made of various materials are in good agreement with the predictions of the theory.

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I. INTRODUCTION

Of fundamental importance in the problem of laser thermonuclear fusion is the question of the effectiveness of the absorption of intense electromagnetic radiation by the plasma. Estimates and numerical calculations show that the energy of the laser pulse E_l required to obtain positive output depends very strongly on the absorptivity of the plasma ε. In the region of values of the released thermonuclear energy E_{tn} comparable with E_l, the necessary energy of laser radiation is proportional to ε^{-4}. At $E_{tn}\gg E_l$, the dependence of E_l on ε is somewhat weaker. However, even in this case, it cannot be neglected.

The absorptivity of a plasma is determined by a large number of processes, the relative role of which depends on the parameters of the plasma and the intensity of the laser radiation. At high intensities and high plasma temperatures corresponding to them, collective processes of absorption and scattering of light associated with the excitation of plasma waves become dominant.[1,2] In this case the generation of fast electrons is a very important circumstance. The level of required energy of the laser pulse also depends very strongly on their presence.

Processes of anomalous absorption were studied theoretically and experimentally in Refs. 3–6. It has been made clear that, in the range of radiation intensities 10^{13}–10^{14} W/cm^2, at a wavelength $\lambda = 1.06$ μ and 10^{11}–10^{12} W/cm^2 in the case $\lambda = 10.6$ μ, the absorptivity has a tendency to increase with increasing intensity, which is characteristic of collective absorption mechanisms. However, a very significant scatter is observed in the numerical values of the absorption coefficients obtained by the different authors. In a number of cases, this scatter, as well as the dependence of the absorptivity on the geometry of the experiment, can be explained qualitatively by refraction effects. The peculiarity of the present situation lies in the fact that, although qualitative agreement between the observed absorption coefficients and theoretical calculations is undoubted (a fact considered in a number of papers as proof of the anomalous character of the absorption), we cannot speak of any quantitative agreement at the present time.

It is essential to note that at the present time there is a whole series of effects that are due to excitation of plasma waves, the observation of which admits of a more definite interpretation and allows us to draw some concrete conclusions on the state of the plasma. Among these effects are the generation of harmonics in the light scattered by the plasma, the most interesting and nontrivial phenomenon being the penetration into the reflected radiation of a signal at the frequency $(3/2)\omega_0$ (ω_0 is the operating frequency of the laser). Generation of the harmonic $(3/2)\omega_0$ was first observed in Ref. 7, and subsequently in our research.[8] Further investigations of the non-linear reflection were carried out by Basov and Krokhin,[9] by ourselves,[10] and by others. Principal attention has been devoted to the study of the dependence of the spectrum and of the energy characteristics of the reflected radiation on the intensity of the incident light and on the focusing conditions. Attempts at explanation of the observed regularities amounted essentially to the general statement that the nonlinear reflection is due to the development of parametric instabilities.

In the present work, the problem of the generation of harmonics is studied in more detail. An attempt is made to interpret the features of the spectrum of the radiation scattered by the plasma, assuming fully defined mechanisms. Special attention is concentrated here on the study of the harmonic $(3.2)\omega_0$, the appearance of which is accounted for with great certainty by the development of an instability that leads to the decay of the initial transverse electromagnetic wave into two plasma waves with approximately equal frequencies.

II. EXPERIMENTAL ARRANGEMENT AND METHODS OF MEASUREMENT

The experiments on the interaction of intense laser radiation with a plasma were carried out on the appara-

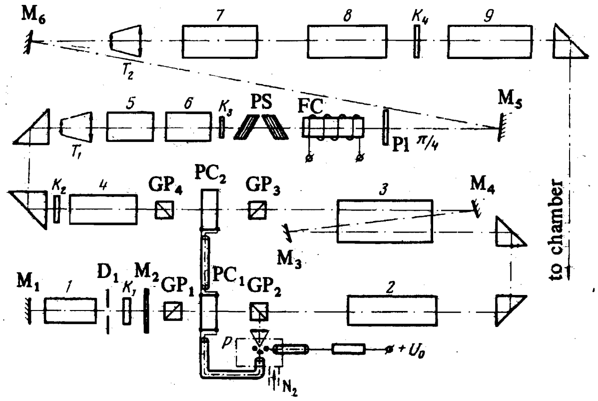

FIG. 1. Diagram of laser system of the setup "Mishen' I." M_1–M_6—mirrors, D_1—diaphragm, K_1–K_4—passive dye shutters, PC_1–PC_2—Pockels cells, GP_1–GP_4—Glan prisms, T_1, T_2—telescopes, PS—polarizer stack, FC—Faraday cell, P—high pressure discharge with laser ignition, 1—master oscillator, 2–9—amplifier stages.

tus "Mishen' I," the scheme of which is shown in Fig. 1.

The single-channel neodymium laser consists of a master oscillator, a pulse-shaping system and amplifier stages with the active elements in the form of rods of circular cross section. The diameter of the active element in the final stage was 45 mm. The amplifier stages were separated by passive decouplers to suppress superluminescence and improve the energy contrast. A Faraday shutter was used to shield the master oscillator and the optical elements of the pulse-shaping system from radiation reflected from the plasma and propagated in the direction counter to the original laser beam. A detailed description of the individual elements of the laser system of "Mishen' I" can be found in our previous work.[8] The characteristics of the light beam, measured at the output of the final amplification stage, are given in Table I.

The construction of the vacuum interaction chamber, the unit for mounting the target, and the location of the diagnostic apparatus are all shown in Fig. 2. The vacuum system guaranteed a rapid evacuation of the chamber to pressures of 10^{-5}–10^{-6} Torr. A focusing lens of diameter 50 mm, with a focal length of 170 mm, is located inside the vacuum chamber. The positioning of the surface of the target in the focal plane of the lens was accomplished by moving the target along the direction of propagation of the light beam (movement by means of a micrometer screw made it possible to assure a target setting accuracy within 20 μ). The laser radiation was focused on the surface of solid plane targets having the shape of discs with diameter 15–20 mm. Targets of aluminum, lead, lithium deuteride (LiD), polyethylene ($(CH_2)_n$) and deuterated polyethylene ($(CD_2)_n$) were employed. The rotation of the target relative to an axis parallel to the axis of the light beam made it possible to make 10–12 successive exposures on each disc under the same focusing conditions without change in the target and breaking the vacuum in the chamber.

TABLE I.

E_{max}, J	τ_p, nsec	τ_{pr}, nsec	Energy contrast	Divergence, rad
50	3.5	<1.0	$>10^4$	$5\cdot10^{-4}$

The maximum density of the intense laser radiation on the surface of the target amounted to 4×10^{14} W/cm^2 (in the focal plane of the lens).

For the study of the basic regularities of the processes responsible for the anomalous light absorption by the plasma, greatest interest is undoubtedly associated with the spectral measurements of the scattered radiation. However, correct interpretation of the results is possible only by their comparison with the results of independent measurements of the plasma parameters, carried out with the necessary time and space resolution. Only experiments over a wide range of laser-pulse intensities under various focusing conditions and with the use of targets of different materials will apparently make it possible to distinguish among the set of complex phenomena which play a role in the laser plasma.

A wide selection of diagnostic apparatus was used in the research. These made it possible to record simultaneously, in each experiment, the basic parameters of the laser pulse, the radiation scattered by the plasma in the visible and infrared regions of the spectrum, and also the x-radiation of the plasma. The spectral composition of the incident light beam and the radiation reflected into the aperture of the focusing lens in the range of wavelengths near the operating wavelength of the laser (1.06 μ) were analyzed with a standard spectrograph STÉ-1. To record the shape and energy of the light pulses, coaxial photocells (FÉK-15) and calorimeters were used. The study of the spectra of the scattered plasma radiation, integrated over the time, at the frequencies $2\omega_0$ and $(3/2)\omega_0$ was carried out with a diffraction spectrograph with electron-optical light amplification. The time variation of the intensity of radiation of the harmonics $2\omega_0$ and $(3/2)\omega_0$ was studied with the help of the monochromator MDR-2 and photomultiplier ÉLU-FT, the signals from which were fed to the oscillograph 6LOR-04 (the time constant of the transient re-

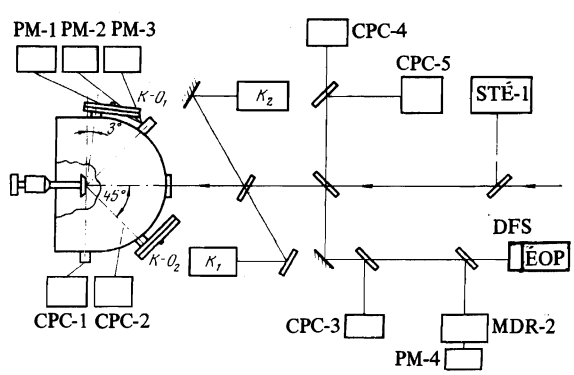

FIG. 2. Interaction chamber and diagnostic apparatus: K_1, K_2—calorimeters, STÉ-1—spectrograph, MDR-2—monochromator, DFS-ÉOP—spectrograph with image converter, PM 1–4—photomultipliers of the ELU type, CPC 1–5—coaxial photo cells, KO_1–KO_2 pinpoint cameras.

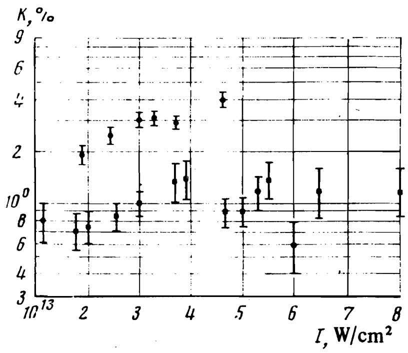

FIG. 3. Dependence of the reflection coefficient of the plasma on the intensity of the incident radiation: ●—polyethylene target, ■—aluminum target.

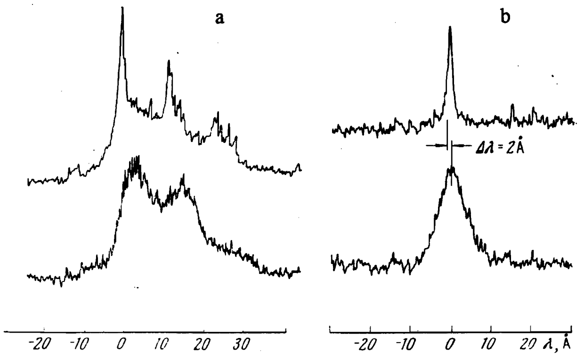

FIG. 5. Characteristic intensity distributions in the spectra of incident (upper) and reflected (lower) radiation: a—"broad" spectrum, b—"narrow" spectrum.

sponse of the measuring circuit did not exceed 1.5 nsec). Observation of the scattered light at the frequencies $2\omega_0$ and $(3/2)\omega_0$ was carried out both in the aperture of the focusing lens and also in directions making angles 45 and 90° with the axis of the incident laser light. A standard absorber method was used to estimate the electron temperature of the plasma from the x-radiation (a five-channel system was used with scintillation detectors covered with foil absorbers of different thickness and different composition). The investigation of the spatial distribution of sources of x-radiation in the plasma flare, and also the estimate of the dimensions of the focal spot, were made by two pinpoint cameras with fivefold magnification, each of which had three identical apertures, covered with absorbers of different thicknesses. One of the pinpoint cameras recorded the x-radiation in a direction making an angle of 87°, and the other at an angle of 42° to the primary laser beam direction. The registration of the image was carried out on specially calibrated photographic film, which was sensitive to soft x-rays. The spectral composition of the plasma radiation in the range of energy of the quanta from 1.5 to 2.5 keV was investigated with the help of a spectrograph with a plane crystal (calcium biphthalate, $2d = 26.6$ Å).

III. RESULTS OF EXPERIMENTS

Figure 3 shows the dependence of the reflection coefficients on the intensity of the incident radiation, obtained by use of polyethylene and aluminum targets. In the case of the polyethylene target, beginning with an intensity of 5×10^{13} W/cm², the reflection coefficient fell with increase in the intensity, while the reflection coefficient remained practically constant for the aluminum target over the entire investigated range of light fluxes. We note that the maximum values of the reflection coefficients are not large and amounted to 4, 1 and 0.5% for targets of polyethylene, aluminum, and lead, respectively.

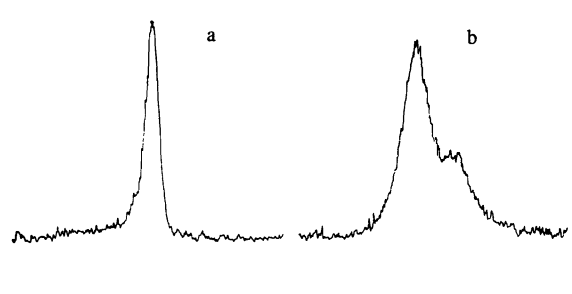

FIG. 4. Typical contours of the lines $2\omega_0$ (a) and $(3/2)\omega_0$ (b).

The spectral distributions of the radiation intensity at the frequencies $2\omega_0$ and $(3/2)\omega_0$ are shown in Fig. 4. Both lines are displaced into the red region of the spectrum. The line shapes are nonsymmetrical as a rule; a mildly sloping descent is observed on the longwave side. The width and the shift of the line $2\omega_0$ undergo practically no change with change in the intensity of the laser radiation. The shift in the $(3/2)\omega_0$ line significantly exceeds the shift in the $2\omega_0$ line, and amounts to 40–80 Å. It can be assumed that the $(3/2)\omega_0$ line has a doublet structure. The shape of the longwave part of the contour of this line changes from experiment to experiment. While the harmonic $2\omega_0$ is reliably recorded when all the enumerated targets are illuminated, when the light fluxes exceeded 3×10^{13} W/cm², we succeeded in observing the $(3/2)\omega_0$ harmonic only in the spectra of plasma scattering from relatively light elements (targets of $(CH_2)_n$ and Al). Upon illumination of lead targets the signal at the frequency $(3/2)\omega_0$ was not observed even for power densities exceeding 2×10^{14} W/cm². It should be noted that the spectral distributions and intensities of the lines $2\omega_0$ and $(3/2)\omega_0$ do not depend on the width and the character of the contours of the spectrum of laser radiation. The characteristic spectra of the incident radiation and the radiation reflected into the aperture of the focusing lens at the frequency ω_0 are shown in Fig. 5.

For targets of Al, we studied the dependence of the intensities of the harmonics $2\omega_0$ and $(3/2)\omega_0$ on the intensity of the laser radiation in the focal spot, I_{inc} (see Fig. 6). The intensity of the harmonic $2\omega_0$ increases in proportion to $I_{inc}^{3/2}$ and the intensity of the harmonic $(3/2)\omega_0$ in proportion to $I_{inc}^{9/2}$.

In calculations of the electron temperature, based on the method of x-radiation with absorbers, calculations were used that were carried out for a homogeneous plas-

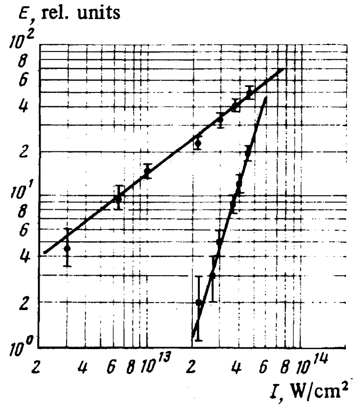

FIG. 6. Dependence of the radiation intensity at the frequencies $2\omega_0$ (●) and $(3/2)\omega_0$ (■) on the density of the incident light flux (aluminum target).

ma with a Maxwellian velocity distribution for the electrons. By choice of suitable filters, parts of the spectrum were cut off that contain the line radiation and the parts near recombination jumps. Then, the obtained values of the "temperature" T_e are certain characteristics of the electron energy distributions, averaged over the entire volume of the radiating plasma. Typical values of T_e obtained in the case of an intensity of the incident radiation ~ 10^{14} W/cm² were as follows: polyethylene—0.6 keV, aluminum—0.5 keV, lead—0.25 keV Upon illumination of aluminum targets, the resonance lines of the hydrogen-like and helium-like ions of Al were recorded with the aid of an x-ray spectrograph (the energies of the quanta $h\nu$, corresponding to these lines, were 1.72 and 1.60 keV). The values of T_e determined from the ratio of their intensities agree in the limits of experimental error with the values obtained by the method of absorbers.

The reduction of the photographs of the plasma jet in the x rays allows us to draw the following conclusions regarding the spatial distribution of the sources of x-radiation. The emission of soft x rays takes place from the dense plasma, which is formed at the surface of the target and not on the walls of the chamber. In observations at an angle of 42° to the direction of propagation of the laser beam, a hot zone was clearly recorded, the diameter of which was equal to ~ 50 μ at optimal focusing of the beam. In the photographs taken at an angle of 87°, only the peripheral, less bright region of the plasma corona is seen. A typical pin-point photograph and the photographic density distribution are shown in Figs. 7a and 7b as an illustration. These correspond to two sections parallel to the surface of the target at distances of 15 and 100 μ from it. Analysis of the microdensitograms of the x-ray images of the plasma corona, obtained for different absorbers (in x rays of different hardness), confirms the correctness of the estimates of the electron temperature and allows us to establish the distribution of the density in the plasma jet. The characteristic size in the direction perpendicular to the surface of the target, on which the plasma density varies from n_{cr} to $n_{cr}/4$, amounted to ~ 60 μ for the aluminum target and ~ 80–100 μ for targets of polyethylene. In the region of space where the density changes from n_{cr} to $n_{cr}/4$, the plasma temperature is practically constant.

IV. DISCUSSION OF THE RESULTS

We now discuss the possible interpretation of the results of the measurements that have been carried out, concentrating attention on two basic questions: the mechanism which assures high absorptivity to the plasma, and the mechanism of generation of the harmonics $2\omega_0$ and $(3/2)\omega_0$. For the answers to these questions, we turn, first of all, to the measurements of plasma temperature. As the results of these measurements show, the ordinary bremsstrahlung mechanism should make a significant contribution to the absorption in the studied cases. Regarding a sufficiently high contribution to the absorption by anomalous processes, we can speak in our experiments only in the case when targets of polyethylene were used and the plasma temperature was sufficiently high. A maximum was observed in this case on the plot of the reflection coefficient against the intensity of the illumination (see Fig. 3). Beginning with an intensity corresponding to the maximum value, the reflection coefficient falls off rather sharply, which, as will be seen from the estimates given below, corresponds to an evident "turning on" of the anomalous absorption. We note that the curve with maximum reflection is similar to the curve with maximum absorption, given in the work of Fabre and Stenz,[5] in which the presence of a minimum is interpreted as a transition to a nonclassical absorption mechanism.

As is known, in the reflection of radiation from an inhomogeneous plasma layer, the parameters of the plasma in the immediate vicinity of the point with electron concentration $n_e \approx n_{cr}$ play a decisive role, i.e., near the point at which the permittivity $\varepsilon(\omega_0)$ tends toward zero. Numerous estimates of the reflection coefficient of the inhomogeneous plasma layer[11–13] lead to the result $R \approx \exp(-2L/c\tau_{ei})$, where L is the characteristic length over which the plasma density changes significantly, c is the velocity of light, and τ_{ei} is the time of electron–ion collisions. It is then easy to obtain

$$R \approx \exp(-1.2\cdot 10^6 ZL/T_e^{3/2}); \qquad (1)$$

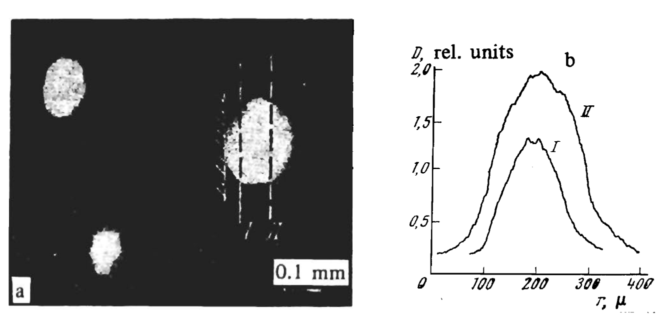

FIG. 7. a) X-ray photograph of the plasma flare, taken at an angle of 87° to the laser beam. Aluminum target, E_{inc} = 20 J, τ = 3.5 nsec. At the right, the hole of the pinpoint camera is covered by foil of thickness 6 μ, to the left, above, by foil of 8 μ, to the left, below, by foil of 12 μ. b) Distribution of the photographic densities along the directions shown in Fig. 7a (I—at a distance of 15.0 μ, II—at 100 μ from the surface of the target).

here Z is the effective charge of the ions, and T_e is the electron temperature in electron volts. We recall that in the illumination of polyethylene targets $T_e \approx 0.6$ keV; $Z \approx 3.5$ and the estimate of L from the results of photometry of the pin point pictures, taken for different absorbers, leads to a value $L \approx 100\ \mu$. Substitution of these quantities in (1) gives $R \approx 0.05$. As is seen from the curve shown in Fig. 3, this result agrees well with the maximum value of the reflection coefficient in the case of a laser-radiation intensity at the target $\sim 5\times10^{13}$ W/cm^2. Increase in the intensity of the radiation and, consequently, increase in the plasma temperature, should, according to (1), lead to an exponential growth in the reflection coefficient. In the experiment, on the other hand, at intensities exceeding 5×10^{13} W/cm^2, a decrease is observed in the reflection, and can be naturally attributed to the development of parametric instabilities.

We now consider some processes of excitation of plasma waves and compare the theoretical value of the threshold intensities for these processes with the obtained experimental data. For our experiments, greatest interest attaches to two processes of parametric excitation of plasma waves under the action of a strong alternating pump field: the decay of the transverse electromagnetic wave into longitudinal and ion-sound waves $t \to p + S$, and the decay of the pump wave into two longitudinal plasma waves $t \to p + p$. Both processes have thresholds in the pump intensity. The minimum threshold of the first process is achieved at a density of the electrons of the plasma close to the critical value, determined by the condition $\omega_p = \omega_0$ (ω_p is the plasma frequency). For the second process, the minimum threshold corresponds to an electron density $n_{cr}/4$. The use of the known theoretical estimates for the threshold intensities[1,14] allows us to show that the maximum intensities of the pump under our conditions exceeds the threshold values in a number of cases and therefore the indicated decay processes should appear and play a decisive role in the absorption of the laser radiation.

We now consider in more detail the process in which the pump wave decays into two plasma waves. Even under those conditions in which the bremsstrahlung mechanism assures practically complete absorption of the light in the region in which the plasma density $0 < n_e < n_{cr}/4$, only about 1% of the radiation is absorbed. As has already been pointed out above, the absorption takes place near the point with $n_e = n_{cr}$ or, more accurately, in a band bounded by values of n_{cr} and $n_{cr}/4$. (Calculations show that in the case of the absorption coefficients observed, the intensity of the radiation in the reflecting layer with $n_e = n_{cr}$ is smaller at threshold than in the layer with $n_e = n_{cr}/4$. The known theoretical results show[1,14,15] that the inhomogeneity has little effect on the instability threshold for the characteristic value $L \sim 10^{-2}$ cm. This allows us to use the relations proposed by Rubenchik[15] for a homogeneous plasma, which lead to the threshold values of the intensities for the decays $t \to p + p$, equal to 3×10^{12} W/cm^2 (polyethylene), 10^{14} W/cm^2 (aluminum) and 4×10^{14} W/cm^2 (lead). The values thus calculated are in excellent agreement with the experimental data. Actually, at an intensity corresponding to the maximum on the reflection curve, the instability threshold for the polyethylene target was exceeded by a factor of 10 and a significant anomalous absorption occurred, much greater than the bremsstrahlung. The harmonic $(3.2)\omega_0$ is observed here in reflected light.

In the case of the aluminum target, the intensity is close to threshold and, although we have succeeded in recording radiation at the frequency $(3/2)\omega_0$, the contribution of the anomalous absorption is small. It must be noted that the value of the intensity averaged over the focal spot was measured in the experiment; the maximum intensity can be several times larger and at some points of space it significantly exceeds the threshold value. It is also impossible to exclude the previously considered[16,17] possibility of self-focusing of the radiation in the plasma. The extraordinarily sharp dependence of the intensity of the harmonic $(3/2)\omega_0$ on the density of the light flux is decisive proof of the threshold situation in the case of illumination of the aluminum targets (see Fig. 6). The concepts developed below lead to the dependences $I_{(3/2)\omega_0} \sim I_{\rm inc}^{3/2}$ if the value of the threshold intensity is surpassed to a sufficient degree. The experimentally obtained dependence $I_{(3/2)\omega_0} \sim I_{\rm inc}^{9/2}$ finds no explanation if we do not assume that the excitation of the instability occurs near threshold. And, finally, in the case of the use of a lead target, the $(3/2)\omega_0$ harmonic is not observed, which is entirely understandable if we take into account the value of the threshold of decay of the photon into two plasmons for this material and attribute its appearance to this process.

We now discuss the mechanism of generation of light with the frequency $(3/2)\omega_0$. Two possible processes can be assumed: the coalescence of three plasmons with frequencies $\sim \omega_0/2$, $p + p + p \to t$, and a process analogous to some degree to Raman scattering, in which the incident photon with frequency ω_0 interacts with a plasmon with the formation of the photon $(3/2)\omega_0$, $t + p \to t'$. As is known, in ordinary Raman scattering of laser radiation of a plasma, the second possibility is absent.[1,18] Therefore, preliminary formation of plasmons with frequency $\omega_0/2$ is necessary within the framework of the mechanism discussed for the generation of radiation with frequency $(3/2)\omega_0$. It is natural to assume that the density of such plasmons is determined by the increase in the parametric instability, i.e., in the case of significant excess over threshold, proportional to the square root of the pump intensity.[15] Hence, both for the interaction photon–plasmon and for the coalescence of three plasmons, we can expect the same dependence $I_{(3/2)\omega_0} \sim I_{\rm inc}^{(3/2)}$.

In the absence of any additional prohibitions, the three-plasmon process is the less probable, if only because not all the photons of the incident radiation decay into plasmon pairs. Generally speaking, there are such prohibitions. It is known that the plasma waves that arise in the decay of the pump wave have sufficiently long wave vectors **k**. The limitation on the value of the wave vector is connected with Landau damping and leads to the result that plasmons are generated in practice with $kr_D \lesssim 0.1$ (r_D is the Debye radius). At the same time, the plasma waves with $k \sim 0.1/r_D$ cannot take part in the process $t+p \to t'$, since both electromagnetic transverse waves have significantly smaller $\mathbf{k}$. This means that the equation of momentum conservation $\mathbf{k}_t + \mathbf{k}_p = \mathbf{k}_{t'}$ is not satisfied. However, a whole series of nonlinear processes is known,[19] for example, the induced scattering of plasma waves by ions, which leads to a concentration of the plasmons in a region smaller than $\mathbf{k}$. In this case, in view of the weak dispersion, the frequency of the plasmons does not change appreciably. Such a process has a number of important consequences; it produces, in particular, the development of specific mechanisms of plasma wave dissipation. For us, however, it is important that, as a result of this process, there are plasmons with a frequency somewhat smaller than $\omega_0/2$, and with a wave vector comparable with the wave vector of the photon. Such plasmons can take part in the generation of radiation whose frequency should be shifted into the red region relative to the exact value of $(3/2)\omega_0$.

A rigorous calculation of the shape of the spectral line $(3/2)\omega_0$ involves certain difficulties and can be based only on certain model representations. The qualitative features and, in particular, the line shift toward the red, find natural explanations within the framework of the mechanism discussed. It is easy to calculate the order of magnitude of the line shift of $(3/2)\omega_0$. Actually, we have $\Delta\omega \sim (3/2)\omega_0 k\Delta k r_D^2 \leq 0.01(3/2)\omega_0$, i.e., the relative shift amounts to ~1% of the frequency, which is in agreement with experiment.

We can attempt to explain the generation of the harmonic $2\omega_0$ in similar fashion. However, there is a whole series of possibilities here, associated with the appearance of the ion-sound wave as a result of the decay process $t \to p+S$. Some aspects of the generation of the harmonic $2\omega_0$ have already been discussed.[9,20] They have allowed an explanation of the observed red shift of the line and the correct estimate of its order of magnitude. An unambiguous choice of the mechanism on the basis of the existing experimental data is difficult. The study of the dependence of the red shift on the mass of the ions would be essential here (see Ref. 20).

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