Directivity of scattered light and x rays in a laser plasma

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The directivity of scattered light and x-ray quanta from a dense plasma produced by focusing a linearly polarized laser beam ($\lambda = 1.06\ \mu$) on the surface of a solid target is investigated for a flux $q \lesssim 2\times 10^{14}$ W/cm^2 and a pulse duration $\tau \approx 3$ nsec. It is found that at these fluxes the fraction of light not absorbed by the plasma (on the order of several per cent) is reflected by the plasma specularly for both normal or oblique incidence of the laser beam on the surface of an aluminum or polyethylene target. A considerable fraction of the reradiated (reflected) normally-incident light does not enter the solid angle of the focusing system. An investigation of the time dependence of second-harmonic emission ($\lambda = 0.53\ \mu$) shows that, in contrast to reflected fundamental-frequency light, the intensity of the second harmonic does not oscillate in time. In the 2–4 keV energy range, an anisotropy is observed in the number of x-ray quanta (of the order of 200–300%) in directions perpendicular or parallel to the laser-beam polarization vector. The experimental results are discussed and interpreted on the basis of the theory of parametric action of intense radiation beams on a plasma.

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Besides the task of further increasing the power[3] and efficiency of modern laser installations, an important role in the problem of plasma heating by laser radiation to thermonuclear temperatures[1,2] is played by the determination of the mechanisms whereby high-power laser radiation is absorbed in the plasma corona, and by the study of the influence of each of them on the plasma parameters. This is connected with the need for creating in the target + laser system conditions that can ensure both a high absorption coefficient for the optical energy and an effective transfer of the absorbed energy to the thermal motion of the ions, which is needed for laser thermonuclear fusion.

Earlier experimental studies[4-6] have revealed effects that cannot be explained within the framework of the usual (inverse bremsstrahlung) absorption of light due to Coulomb collisions of the electrons with the ions. These include the constancy or even the decrease of the reflection coefficient R with increasing flux density $q \lesssim 5 \times 10^{13}$ W/cm^2, the generation by the plasma of harmonics of the frequency ω_0 of the heating radiation ($1.5\omega_0$, $2\omega_0$, ...), oscillations of the intensity of the reflected radiation with frequency on the order of 10^9 Hz, etc. This paper reports a continuation of these experiments for the purpose of revealing in greater detail the physics of the interaction of laser radiation of high power with the plasma "corona," Just as in[6], the interpretation of the experimental results is based on concepts of the nonlinear theory of the action of high-power radiation on a plasma.[7,8]

EXPERIMENTAL SETUP

The laser installation and the diagnostic apparatus are illustrated in Fig. 1. The laser setup differed from that described in[6] in that an amplifier stage was added with double passage of the radiation through the rod. The total length of the laser from the total-reflection mirror of the generator to the output end of the last amplifier was approximately 20 m. A light pulse of energy up to 30 J, duration 3–4 nsec at half energy, approximate contrast 10^5, and approximate divergence 5×10^{-4} rad was focused with a lens of focal length 10 cm onto the surface of a target placed at the center of the vacuum chamber. The targets used in this experiment were solid ordinary $(CH_2)_n$ and deuterated $(CD_2)_n$ polyethylene, as well as aluminum. The flux density q averaged over the pulse and over the focal spot reached values of 2×10^{14} W/cm^2. The degree of linear polarization of the radiation was not worse than 90% (the polarization vector was perpendicular to the plane of Fig. 1). The energy and waveform of the incident and reflected pulses were registered with calorimeters and coaxial photocells. The signals from the latter were fed to an oscilloscope. The time resolution was not worse than 10^{-9} sec. To investigate the waveforms of the radiation incident and reflected in various directions we used an electron-optical converter with a time resolution not worse than 10^{-10} sec.

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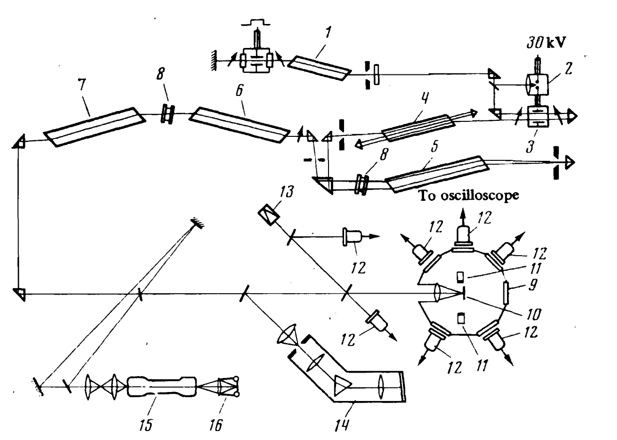

FIG. 1. Experimental setup: 1—neodymium laser Q-switched with a Kerr cell, 2—discharge gap with laser ignition, 3—shaping Kerr cell, 4—three-pass amplifier, 5—two-pass amplifier, 6, 7—one-pass amplifiers, 8—cells with saturable filters, 9—vacuum chamber, 10—target, 11—x-ray detectors, 12—coaxial photocells connected to oscilloscope, 13—calorimeter, 14—prism spectrograph, 15—photoelectronic recorder (FÉR-2), 16—photographic camera.

section of which in the plane perpendicular to the polarization vector of the heating radiation was an irregular heptagon. made it possible to investigate the parameters of the radiation scattered by the plasma in directions lying in this plane and making angles 0, 45, 60, 90, 120, 135, and 180° with the laser-beam axis, and also in a direction parallel to the polarization vector of the incident radiation. This made it possible to investigate the spatial distribution of the radiation reflected (scattered) by the plasma at different orientations of the plane of the target relative to the laser-beam axis, and also to investigate the time structure of the scattered radiation in all the indicated directions.

In addition to the reflected (scattered) light radiation we investigated the spatial distribution of the intensity of x rays passing through beryllium and aluminum filters of various thicknesses. A feature of this experiment was that the x-rays were registered on x-ray film with a sensitivity down to 1 Å (UF-R or UF-VR film), placed in a special cassette, at the entrance of which were mounted absorbing filters with different transmission curves. We used beryllium filters 100 to 2500 μ and aluminum filters 20 to 200 μ thick. The cassettes were oriented at various angles to the target plane, and two or three cassettes were placed in each direction at various distances (from 2 to 10 cm). This made it possible to operate in each flash in the region of normal density of the photographic film, and consequently to obtain information on the distribution of the x-ray intensity (more accurately—on the distribution of the number of x-ray quanta) in any given direction in a wide spectral interval. In addition, this made it possible to obtain in each flash the density curve of the photographic film for each filter (since the number N of the x-ray quanta incident on the photographic film is inversely proportional to the square of the distance r from the cassette to the target, $N \propto r^{-2}$), which is needed to determine the relative intensities of the x-rays in the various directions in the investigated spectral range. The photographic film, measuring 1 × 1 cm, was covered in each cassette with 14 filters of various thicknesses, so that there was about 7 mm^2 of film for each filter, making possible a correct reduction of the results.

DIRECTIVITY OF REFLECTED RADIATION

The spatial distribution of the radiation reflected from the plasma at various laser-beam incidence angles on the surface of a flat target was investigated with calibrated coaxial photocells. Figure 2 shows a typical directivity pattern of the reflected radiation in a plane perpendicular to the polarization vector of the laser radiation, for the case of normal incidence of the light beam on the target at a flux density $q \approx 6 \times 10^{13}$ W/cm^2. The reflection coefficients in different directions have been recalculated on this diagram in terms of the aperture of the vocusing lens, which amounted to ≈ 0.64 sr in our experiment. The reflection coefficient R in the aperture of the focusing lens was approximately 0.65%, and when the observation angle α (i.e., the angle between the investigated direction and the laser beam) was increased from 0 to 90° the reflection coefficient decreased very rapidly. For example, when the light scattering was observed in the solid angle subtended by the lens, the reflection coefficient at $\alpha = 90°$ was $R \approx 3.2 \times 10^{-3}$%. Observation of the reflected radiation at an angle 90° in a direction parallel to the polarization vector gave approximately the same value of the scattered energy, thus indicating that the scattering of the laser radiation by the plasma at 90° to the laser-beam axis is isotropic at the flux densities of this experiment. This result, in conjunction with the effect of the anomalously high (non-bremsstrahlung) absorption[6] of high-power laser radiation by a dense plasma allows us to conclude that under the conditions of our experiment the nonpotential parametric instability of the stimulated Mandel'shtam-Brillouin scattering (SMBS) does not appear in the theoretically predicted angle region.[9] Indeed, according to Galeev et al.,[9] SMBS of high-power radiation occurs mainly at an 90° to the radiation propagation direction.

In spite of the fact that the directivity pattern of the reflected radiation is strongly elongated in the direction of the focusing lens and the energy of the reflected radiation back is much higher than for the other directions, allowance for the radiation scattered in all directions leads to a noticeable increase of the fraction of the energy reflected from the plasma. For example, in the case shown in Fig. 2, integration of the directivity pattern over the half-space in front of the target leads to a value $R \approx 3\%$ for the total coefficient of reflection into a solid angle 2π sr. It should be noted that in practically all the experiments in which the coefficient R of reflection from the plasma was investigated (see the references in[4] and also the articles[10-12]) they measured the reflected light flux only in the solid angle of the focusing system. This measurement yields only the lower limit of the reflected energy and can lead to an appreciable error when it comes to determining the fraction of the laser-beam energy absorpted in the plasma.

An investigation of the time structure of the reflected radiation has shown that, just as at lower light fluxes (see[6]), modulation of the reflected-pulse intensity takes place, and not only for observations at the angle $\alpha = 0°$ but also at other angles. The period of the oscillations of the envelope of the light pulse was the same for different observation angle α and amounted to $\tau \geq 1$ nsec, while the depth of modulation, which reached 50% in some flashes, was apparently maximal at $\alpha = 45°$.

The oscillations of the intensity of the reflected radiation are due to relaxation oscillations of the level of the nonstationary parametric turbulence, initiated by an instability of the type of $t \to l + s$ decay of the light wave into an electronic Langmuir wave (plasmon) l and an ion-sound wave s in the vicinity of the critical value of the plasma density (cf.[13]). The period of such oscillations is given by the expression (cf. formula (4) of[6])

$$\tau \approx 10^2 \frac{\omega_p}{\omega_{Li}^2} \frac{r_{Di}}{r_{De}} \left(\frac{q}{q_{\text{thr}}} - 1\right)^{-1} \left(\frac{\omega_{Li}^2}{\omega_p^2} + 6\frac{\omega_0 - \omega_p}{\omega_p}\right)^{1/2} \times \left[\left(\frac{\omega_{Li}^2}{\omega_p^2} + 6\frac{\omega_0 - \omega_p}{\omega_p}\right)^{1/2} - \frac{\omega_{Li}}{\omega_p}\right]^{-1}, \quad t \to l + s. \tag{1}$$

Here ω_p is the plasma frequency, ω_{Li} and ω_0 are the ion-Langmuir and the laser-radiation frequencies, r_{Di} (r_{De}) are the Debye radii of the ions (electrons), q_{thr} is the threshold value of the light flux q incident on the plasma for the instability $t \to l + s$. Formulas (1) and (4) of[6] are quite different in their structure. However, estimates obtained from them for the period of the oscillations under the conditions of our experiment yield values close to the observed ones ($\tau \sim 1$ nsec).

The oscillations of the reflection coefficient can also be connected with gasdynamic phenomena in the laser plasma, for example with the time evolution of nonlinear deformations of the nonmonotonic density profile. These deformations can stem, for example, from various effects due to the force exerted by the light field or by the internal plasma field on the charged particles (cf.[15,16]). To explain the process causing the oscillation of the reflected radiation it is necessary to carry out a joint analysis of experimental data that seem different at first glance. It is therefore of interest to study the temporal structure of the emission of harmonics of the heating light wave by a laser plasma.

In this experiment we investigated the time behavior of the line of wavelength $\lambda = 0.53\ \mu$ corresponding to the second harmonic of the radiation incident on the target, and propagating in the solid angle of the focusing lens at normal incidence of the radiation on the surface of flat polyethylene and aluminum targets. To this end the 0.53-μ radiation was focused, either through interference filter or from the exit slit of the spectrograph, on the entrance slit of an FÉR-2 photoelectronic recorder, which provided a time scan with a resolution not worse than 10^{-10} sec. The reduction of several dozen of the scans made it possible to conclude that the waveform of the plasma radiation at the second-harmonic wavelength duplicates approximately the envelope of the reflected pulse at the fundamental frequency, but in none of the flashes did we observe modulation of the radiation intensity at the second-harmonic frequency.

According to the present premises of the theory of second-harmonic radiation from a plasma,[17,18] the light wave t at double the frequency, $2\omega_0$ of the laser-radiation incident on the plasma is the result of the coalescence of either two electronic Langmuir oscillations, $l + l \to$ t, or of one electron Langmuir oscillation and a light wave, $l +$ t $\to$ t. The latter process, $l +$ t $\to$ t, must of necessity lead to oscillations of the second-harmonic intensity if the light signal that takes part in it is reflected and oscillates in time, in accord with the measurement results, regardless of the interpretation variant employed. It remains therefore to propose that the second harmonic $2\omega_0$ observed by us is either the result of the coalescence of an electron Langmuir oscillation and the light wave incident on the plasma, or the result of the coalescence $l + l \to$ t of two such electron Langmuir oscillations, the electric energy density of which does not oscillate in time. The latter possibility of a non-oscillatory time dependence of the energy density of the electron Langmuir oscillation exists, for example, whenever the oscillations l are produced by transformation of a laser beam by the density gradient of the plasma produced by it, or by parametric instability, but in such a way that their level depends essentially on the density gradient and on the outflow of the oscillation energy from the parametric-buildup zone; this outflow leads to a monotonic (nonoscillating) change of the level with time (cf.[19,20]).

It should also be noted that the time scan of the second-harmonic intensity was obtained in this experiment only at fluxes $q < 10^{13}$ W/cm^2. The use of higher-power fluxes can alter the picture in principle, although an investigation[21] of the time behavior of the intensity of the harmonics $2\omega_0$ and $1.5\omega_0$ revealed no oscillations at light fluxes $q \sim 10^{16}$ W/cm^2 for a neodymium laser with a pulse duration approximately one-tenth of that used by us.

Another important fact observed in this experiment is the specular character of the reflection in the case of oblique incidence of the radiation on a flat target. Figure 3 shows a typical directivity pattern of the reflected (scattered) radiation for the case when the aluminum target was inclined 45° to the laser beam, with the polarization vector located in the target plane. The diagram is elongated in the direction 90° relative to the laser beam, and the integral reflection coefficient agrees within a factor of two, with the reflection coefficient obtained in the case of normal incidence. The fraction of the energy reflected in the solid angle of the focusing system was smaller than the parasitic reflection from the latter, i.e., less than 0.1% of the laser energy. The experimental point corresponding to reflection from the focusing system is marked on Fig. 3 on the axis of the radiation incident on the target. The arc drawn through this point indicates the aperture of the focusing lens, in terms of which the reflection coefficients in various directions have been recalculated.

The effect of the specular reflection (scattering) of the laser radiation by the target is in contrast to the results of Eidmann and Sigel,[10] who found that each ray of the laser beam is reflected back by the plasma along the direction of incidence on the target surface, i.e., not at all specularly. It must be borne in mind, however, that in contrast to the experiments described in this section, their experiments were performed only at normal incidence of the radiation on a deuterium target.

The experimentally observed specular character of the scattering (reflection) of high-power laser radiation by a high-temperature dense plasma, in conjunction with

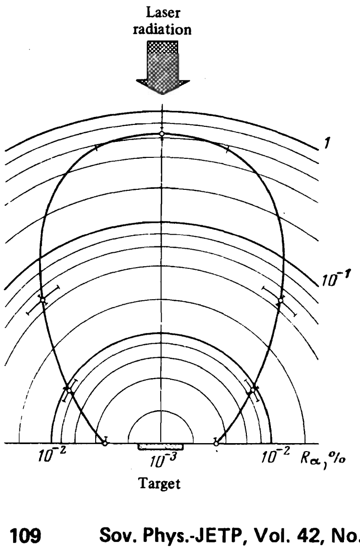

FIG. 2. Typical directivity pattern of reflected radiation in a plane perpendicular to the polarization vector of the laser-radiation polarization, for the case of normal incidence of the light beam on the target at a flux density $q \approx 6 \times 10^{13}$ W/cm^2 (the arcs drawn through the experimental points indicate the aperture of the registering photocells).

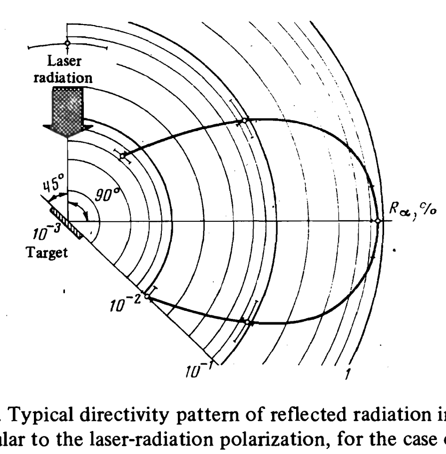

FIG. 3. Typical directivity pattern of reflected radiation in a plane perpendicular to the laser-radiation polarization, for the case of incidence of the light beam on the target at 45°, at a flux density $q \approx 7 \times 10^{13}$ W/cm^2 (the arcs drawn through the experimental points indicate the apertures of the recording photocells).

the anomalous-absorption effect,[6] raises in the theory the question of the relative contribution of the ordinary linear reflection of light radiation from a plasma region having a density higher than critical and playing the role of a mirror in a wide range of fluxes, and of the nonlinear reflection that supplements the anomalous absorption. The turbulent character of the anomalous absorption does not exclude the possibility of this absorption being anisotropic, meaning also the possibility of the existence of a perfectly defined scattering pattern for above-threshold light flux. A clear-cut quantitative answer to this question might be provided by a nonlinear theory of the action of high power radiation on a plasma, in which account is taken of the influence of anisotropic parametric turbulence on the angular distribution of the absorbed and scattered light energy relative to the direction of the polarization vector or the propagation of the light beam. The answer can be formulated qualitatively even now. Namely, in the range of the light fluxes used in the experiment described above, which exceed the minimal threshold flux by one or two orders of magnitude at an absolute value of the measured reflection coefficient not larger than several per cent, the effective value of the imaginary part $\epsilon''(\omega_0)$ of the dielectric constant of the laser plasma, which is determined by the effective frequency ν_T of the anomalous absorption, while exceeding the Coulomb value significantly, is still small, as before, in comparison with the real part $\epsilon'(\omega_0)$ of the dielectric constant in a wide range of detunings $(\omega_0 - \omega_p)$. In this sense, the light fluxes used in the experiment should be reflected by the laser plasma in accordance with laws close to those determined by the classical Fresnel formulas, i.e., specularly (by that part of the plasma whose density is higher than critical).

The experimentally established high level of anomalous (nonlinear) absorption, in conjunction with the specular character of the reflection, is evidence of the productivity of the concept introduced in the theory of[22], that of scalar (independent of the light-beam propagation direction) effective frequency ν_T of the nonlinear absorption of the intense electromagnetic wave due to parametric turbulence. We emphasize also that it is precisely by virtue of the time-oscillating character of the anomalous absorption $\nu_T(t)$ the envelope of the pulse of the specularly reflected weak light flux turns out to be modulated in time at the same frequency which was measured previously[6] in the study of the reflection of laser radiation into the solid angle subtended by the lens.

ANISOTROPY OF THE X RADIATION FROM THE LASER PLASMA

As noted above, the continuous x radiation from the plasma was registered with high-sensitivity x-ray films placed in cassettes, a typical arrangement of which as shown in Fig. 4. This method of registration of continuous x radiation provides in general no temporal resolution. This circumstance, however, does not affect significantly the results of the measurements of the total number of x-ray quanta during the time of the laser pulse. In a laser plasma, the temperature decreases rapidly after the termination of the laser pulse, the electron temperature decreasing in inverse proportion to the square of the plasma dimension. The power of both the bremsstrahlung ([23], p. 194) and the recombination ([24], p. 441) radiation, integrated over the spectrum, decreases because of the decrease of the temperature and of the recombination-induced decrease of the effective plasma-ion charge. Since the x rays registered in the experiments are at the short-wave end of the spectrum, the rapid decrease of the registered signal after the termination of the laser pulse is due also to the shift of the radiation spectrum towards longer wavelengths.

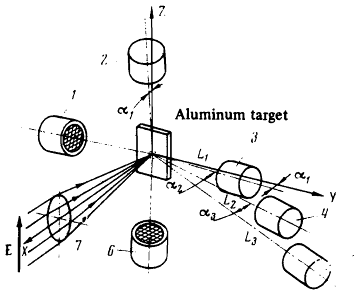

FIG. 4. Arrangement of multichannel x-ray detectors (1–6) relative to the target; $\alpha_1 = 5°$, $\alpha_2 = \alpha_3 = 10°$; 7–lens.

Thus, the overwhelming majority of the quanta registered by the x-ray film are emitted by the plasma during the laser pulse. At the same time, the registration method widely employed in laser-plasma diagnostics, by means of a scintillator that converts the x rays into visible light and by means of a photomultiplier, does not afford a time resolution better than 3–4 nsec. The reason lies both in the finite time of the scintillations and in the parameters of the existing photomultipliers. Therefore a method in which photomultipliers are used offers no advantages if the quantum energy of the registered x-ray is less than 10 keV. This method is needed only for the registration of higher-energy quanta, i.e., beyond the sensitivity limits of the presently available x-ray films.

On the other hand, the method of registration with x-ray films has many important advantages, such as high reliability of the registration process and compactness of the recording detectors, so that measurements can be performed in an almost unlimited number of channels. The number of quanta per detector can be varied in a wide range by placing the detectors in one direction at various distances from the investigated plasma (an attenuation by two orders of magnitude was possible at the geometry of the described experiment); the dynamic range of the procedure can be appreciably expanded by using films of varying sensitivity. As a result of all this we were able to operate in the region of normal film density in practically every flash, and obtain information on the spectral distribution in a sufficiently wide range without preliminary calibration of the detectors.

In the reduction of the measurement results obtained with x-ray films it was observed that, starting with flux densities $q \geq 2 \times 10^{13}$ W/cm^3, a noticeable anisotropy of the x-radiation is observed, manifest in the fact that the plasma emits noticeably more quanta in the plane of the target, in a direction perpendicular to the electric field vector **E** of the light wave, than in a direction parallel to **E**. The anisotropy was observed in 118 out of 259 flashes at $q \geq 2 \times 10^{13}$ W/cm^2, corresponding to approximately 43% of the cases, and in not one of the flashes did the number of quanta in the direction parallel to **E** exceed the number in the perpendicular direction, even within the limits of the measurement error. It must be borne in mind that the percentage of flashes with anisotropy was apparently even higher, since in some of the cases, which we assume to be isotropic, only films with filters more than 2000 μ thick corresponded to the region of normal density, and in this spectral band the radiation was isotropic also in flashes with anisotropy (see Fig. 6).

Figure 5 shows photographs of films in which the number of quanta passing through filters of various thicknesses, in two directions, were registered. Figure 6 shows the dependence of the degree of anisotropy ζ on the thickness of the beryllium filter δ (or, equivalently, on the transmission end-point energy E_{ep} of the filter, corresponding to attenuation of the x-rays in the filter by two orders of magnitude), using the flash of Fig. 6 as an example. The anisotropy is defined as the ratio $\zeta \equiv DN_{\perp}/dN_{\parallel}$ of the numbers $dN_{\perp}$ and $dN_{\parallel}$ of the x-ray quanta emitted by the laser plasma into the solid angle dO_k in directions perpendicular ($dN_{\perp}$) and parallel ($dN_{\parallel}$) to the electric field vector **E** of the light beam. It is seen from Fig. 7 that the degree of anisotropy is maximal for thin filters and tends to unity (the x-radiation is isotropic at $\zeta = 1$) with increasing filter thickness δ, i.e., with increasing end point energy E_{ep}. The anisotropy reaches a maximum value 200–300% ($\zeta = 2-3$).

The observed anisotropy of the number of x-ray quanta from a laser plasma is the main experimental result of this section.

We discuss now the possible physical causes of the x-ray anisotropy. We note first that radiation with a line spectrum, the intensity of which can greatly exceed the intensity of radiation with a continuous spectrum,[24] is not present in the spectral range investigated in the described experiment. Therefore the possible mechanisms that lead to anisotropy of the x rays with the line spectrum will not be discussed here. More natural for the interpretation of the experimental data is the possibility of generation, by the laser plasma, of x rays with a continuous spectrum via free-free transitions, when electrons of sufficient energy emit x-ray quanta as a result of slowing down by collisions with the ions of the laser plasma (bremsstrahlung).

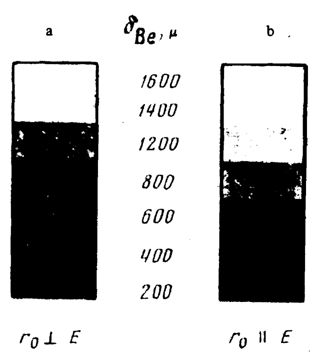

FIG. 5. Photographs of films used to register the x-rays passing through beryllium filters of different thicknesses δ in two directions.

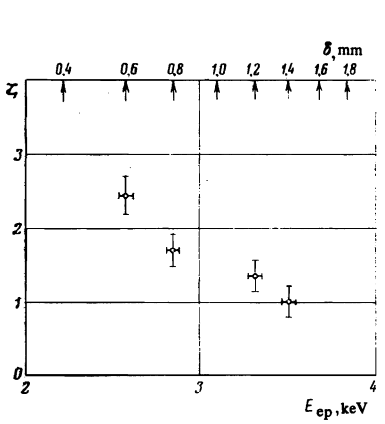

FIG. 6. Dependence of the degree anisotropy ζ of the x rays on the end-point energy E_{ep} of the transmission of a beryllium filter (corresponds to attenuation of the radiation by a factor 10^2 in a filter of thickness δ) for an aluminum target, $q = 5 \times 10^{13}\ W/cm^2$.

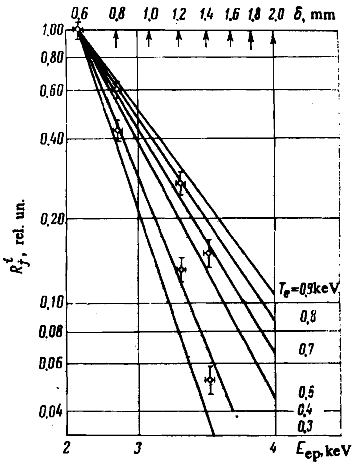

FIG. 7. Dependence of the ratio of the number of quanta passing through beryllium filters of various thicknesses δ on the transmission end-point energy for a flash with emission anisotropy in the case of an aluminum target: •–$(R_j^i)_{\perp}$, ○–$(R_j^i)_{\parallel}$, $R_j^i = N_{\delta i}/N_{\delta j}$; $q \approx 5 \times 10^{13}\ W/cm^2$.

Electrons with velocities higher than the thermal velocity v_{Te} can be produced in a laser plasma along the electric field intensity vector **E** of the light wave in amounts ranging from a fraction of one per cent to several per cent of the total density n_e, as a result of development of parametric instabilities.[25] It can be stated that the parametric instability produces in a plasma acted upon by high-power laser radiation a beam of fast electrons along E. The concrete form of the distribution function δf_e of the fast electrons is determined by the singularities of the corresponding parametric instability. Integration of the bremsstrahlung cross section of the fast electrons with distribution function δf_e as they are slowed down by aluminum ions yields for the number of x-ray quanta with energy in a range from one to ten keV, a value much higher than the number of recombination-radiation quanta, which in turn is larger by two orders of magnitude than the number of bremsstrahlung quanta (in the same energy band) for a Maxwellian electron distribution. This circumstance plays the decisive role in the appearance, in the described experiment, of the anisotropy of the x-ray angular distribution, which is typical of a nonrelativistic electron beam.

For a quantitative illustration of the foregoing considerations we present simple relations for the angular distribution of the number of naturally polarized x-ray quanta with wave vector **k**, emitted by a laser plasma with an electron beam (see, e.g.,[26], Sec. 90):

$$\delta f_e = \delta n_e \delta(\mathbf{v} - \mathbf{u}), \tag{2}$$

traveling approximately along the polarization vector **E** of the laser beam, $\mathbf{u} \times \mathbf{E} \approx 0$:

$$\frac{dN(\theta)}{dO_k} \equiv \frac{dN_{\perp}}{dO_k}\sin^2\theta + \frac{dN_{\parallel}}{dO_k}\cos^2\theta = \frac{z^2}{\pi}\alpha r_e^2 \frac{c^2}{u}\delta n_e n_i(z)\{I_{\perp}\sin^2\theta + I_{\parallel}\cos^2\theta\}, \tag{3}$$

$$I_{\perp} = 2\int_{x_1}^{x_2} \frac{x^2 dx}{1-x^2}\left[\frac{3-x^2}{2x}\ln\frac{1+x}{1-x} + 1\right], \tag{4}$$

$$I_{\parallel} = 4\int_{x_1}^{x_2} \frac{x^2 dx}{1-x^2}\left[\frac{1+x^2}{2x}\ln\frac{1+x}{1-x} - 1\right]. \tag{5}$$

In these formulas $dN(\theta)$ is the number of x-ray quanta emitted by a unit volume of the laser plasma in a unit time into a solid-angle element dO_k with axis along the wave vector **k** making an angle θ with the electron-beam propagation direction $\mathbf{u} \parallel \mathbf{E}$, $\alpha \approx 1/137$ is the fine-structure constant, r_e is the classical radius of the electron, and c is the speed of light in vacuum. The integration limits x_1 and x_2 in the right-hand sides of (4) and (5)

$$x_1=[1-4\pi c\hbar(mu^2\lambda_{min})^{-1}]^{1/2}, \quad x_2=[1-4\pi c\hbar(mu^2\lambda_{max})^{-1}]^{1/2} \quad (6)$$

determine the width of the spectral interval (with respect to the wavelengths $\lambda = 2\pi/k$ or with respect to the energies $\hbar ck$):

$$\lambda_{min}<\lambda<\lambda_{max}, \quad 2\pi c\hbar/\lambda_{max}<\hbar ck<2\pi c\hbar/\lambda_{min}, \quad (7)$$

in which the x-rays are registered ($\hbar$ is Planck's constant). The experimentally-measured degree of anisotropy $\zeta = dN_\perp/dN_\parallel$ is given, according to relations (3)—(5), by the fraction $I_\perp/I_\parallel = \zeta$ (the x-ray film registered the total number of quanta from the entire volume of the laser plasma during the duration of the laser pulse in a given direction and in a given spectral interval). The total number of x-ray quanta in all directions can be obtained by integrating the right-hand side of (3) with respect to the solid angle dO_k from 0 to 4π.

An estimate of the degree of anisotropy ζ with the aid of formulas (2)—(7) gives satisfactory agreement with the experimental result $\zeta \approx 2-3$ if the relative number $\delta n_e/n_e$ of the fast electrons with kinetic energy ~ 10 keV is on the order of a fraction of one per cent, and the x-ray energy lies in the range 1—10 keV. This agreement demonstrates the productivity of the assumption made above that the bremsstrahlung is the mechanism whereby the x rays are emitted by the fast electrons produced in a laser plasma by the parametric instability. We shall therefore dwell in somewhat greater detail on this mechanism. According to[6,8], the threshold fluxes q_{thr} of the laser radiation for the development of periodic and aperiodic potential instabilities in an aluminum plasma with density n_e close to the critical $n_e \approx 10^{21}$ cm^{-3} for a neodymium laser lie in the range $\sim 10^{12}-10^{13}$ W/cm^2, depending on the type of instability and on the relative contribution of the effects of dissipation and of the inhomogeneity of the laser plasma.

Under the conditions of our experiment, the fastest to grow is the amplitude of the plasma oscillations that propagate in a direction parallel to **E**. This growth, in conjunction with one of the mechanisms of the linear[19,20], quasilinear,[8,27,28], or nonlinear[9,13,14,22] saturation raise the plasma to a turbulent state with a sufficiently high level of plasma oscillations, which ensures, in accord with the Cerenkov effect, a quasilinear deformation of the electron distribution function in the region of velocities higher than thermal, $v \gg v_{Te}$, of the order of the phase velocity of the high-frequency plasma oscillations. As a result, the electron distribution function in this velocity range becomes non-Maxwellian and close to the distribution function of electron beams propagating along **E** and having a finite thermal scatter (cf. (2)). The relative number of such fast electrons increases with the laser radiation flux, and under the conditions of our experiment, according to the quasilinear theory of a parametrically unstable plasma, constitute about a fraction of one per cent to one per cent of the total number of electrons in the region of the critical plasma density. This number agrees with the estimate made above. It can be assumed that for an instability such as decay of a light wave into electron Langmuir and ion-sound oscillations, in the approximation of one-dimensional quasilinear relaxation of the parametric turbulence of an isotropic plasma, the fast-electron distribution function is close to that obtained earlier,[29] i.e., it has a power-law form

$$\delta f_e \propto \delta(v_x)\delta(v_y)|v_z|^{-n}, \quad v_z=(\mathbf{vE})E^{-1}. \quad (8)$$

A numerical calculation of the degree of anisotropy ζ for the electron distribution function (8) agrees with the experimental results at n = 4, in the velocity interval $7.5v_{Te} < |v_z| < 25v_{Te}$, and in the x-ray energy range 1.3 keV $< \hbar ck <$ 12 keV.

The performed x-ray measurements together with the described physical idea of their interpretation can be regarded as a diagnostic procedure for the determination of the characteristic parameters of fast electrons in a laser plasma. It must also be noted that by measuring the ratio $R^i_j = N(\delta_i)/N(\delta_j)$ of the numbers $N(\delta_i)$ and $N(\delta_j)$ of the quanta passing through filters of different thicknesses δ_i and δ_j we can determine the plasma electron temperature, by comparing the ratio R^i_j with the theoretical values calculated for the continuous x radiation from the plasma at a Maxwellian distribution in velocity. This method (of absorbers or filters)[30] was first proposed for the measurement of the electron temperature in the "theta pinch," and has been extensively used of late in laser-plasma diagnostics.[31-35]

Measurements were made of the dependence of the ratio R^i_j of the number of quanta passing through filters of different thicknesses on the end-point energy, for a flash in which no anisotropy was observed (the change of the spectral sensitivity of the film was taken into account in accord with the data of Movshev et al.[36]). It turned out that for all the filter combinations, in the investigated spectral range, the ratio R^i_j corresponds to a temperature $T_e \approx 0.5 \pm 0.05$ keV for a plasma with a Maxwellian electron distribution. The temperature T_e determined in this manner for plasma electrons in flashes without anisotropy amounted to $T_e \approx 0.5-0.8$ keV at a flux density $q \approx 5 \times 10^{13}-10^{14}$ W/cm^2.

An analogous relation for a flash with anisotropy is shown in Fig. 7. In this case, when the ratios R^i_j are different for directions perpendicular and parallel to the electric vector **E** of the light wave, the values of the plasma electron temperature T_e determined in this manner also turn out to be different for these directions. The experimental points lie close to the calculated ones for a Maxwellian distribution with a temperature $T_e \approx 0.7$ keV for a direction parallel to E, and $T_e \approx 0.4$ keV for the perpendicular direction. The scatter of the temperatures for each direction increasdd in comparison with the isotropic case and is approximately 25%.

Since the degree of anisotropy decreases with increasing end-point energy E_{ep}, it is obvious that when the investigated interval is extended towards shorter wavelengths the deviation of the values of R^i_j from a Maxwellian distribution for both directions will increase even more. We emphasize in this connection the caution with which we must approach the interpretation of the experimental data obtained on the spectral distribution of x rays from a nonequilibrium laser plasma with the aid of the absorber procedure. If one disregards the anisotropic character of the x rays and no account is taken of the placement of the x-ray detectors when the ratios R^i_j are determined, it is possible to obtain, with the same flash, a set of different distribution functions, neither of which corresponds to reality.

Notice must be taken also of another circumstance. The foregoing comparison of the parametric-resonance theory with experiment shows that a very strong distortion can take place in the spectral and spatial distributions of the x rays from the laser plasma even if the bulk of the plasma electrons have a Maxwellian velocity distribution, and only a negligible fraction (less than one per-cent) has at velocities higher than thermal $v \gg v_{Te}$ have a distribution function close to that of the electron beam. All this forces us to conclude that the absorber method may not be suitable in a number of cases for the measurement of the electron temperature of a laser plasma, even if an extremely insignificant fraction of the electrons have a velocity distribution other than Maxwellian.

We note in conclusion that our results point to an anomalous character of the interaction of high-power light beams with a laser plasma. X-ray measurements in a laser plasma and a detailed comparison with the results of the theory uncover a possibility of revealing not only such a larger-scale laser-plasma characteristic as the temperature of its electrons, but also fine details of the electron distribution function in a wide range of their velocities.

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