Brillouin scattering in a laser plasma at moderate intensities 10^{12}–10^{14} W/cm^2

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Measurements of the space-time and spectral characteristics of the radiation scattered by the plasma during normal and oblique incidence of an intense laser beam at $\lambda = 1.06\,\mu$m with a narrow spectral line (~ 0.1 Å) on plane targets of various materials are reported and discussed. At irradiances above 10^{13} W/cm^2, for targets with a low ion charge Z, the observed broadening of the scattered-radiation spectrum, to 15–20 Å, agrees well with the theoretical predictions of a transition of the instability of stimulated Brillouin scattering into a modified decay instability.

The recent thrust in research on laser controlled fusion has been to search for ways to minimize the energy of the laser systems used to compress and heat the deuterium-tritium fuel in spherical targets. The necessary reduction of the energy of the laser beams can be achieved by raising the efficiency at which the light is absorbed in the plasma corona and by achieving high hydrodynamic compression efficiencies. As the intensity of the laser light at the target surface increases, the classical collisional mechanism for absorption fades in importance, and various nonlinear processes come into play.[1,2]

At high beam irradiances, much of the energy of the absorbed light may be converted into the energy of fast suprathermal electrons, which heat the inner layers of the target and thereby hinder its compression. Interest is accordingly attracted to compression regimes which instead of intense laser beams require only $\sim 10^{14}$ W/cm^2 in pulses with lengths in the nanosecond range. Under such conditions, a steady-state plasma corona with dimensions of a fraction of a millimeter forms near the target. If the density profile is comparatively smooth, however, the conditions which arise in the plasma corona favor the development of stimulated Brillouin scattering and stimulated Raman scattering, which cause anomalously intense reflection and scattering of the laser beam. The most dangerous process under these conditions is stimulated Brillouin scattering, for which the threshold laser intensities are relatively low. Consequently, experimental modeling and a comprehensive study of stimulated Brillouin scattering are exceedingly important to the laser fusion program.

In this paper we report and discuss some experimental results obtained on the Mishen'-1 device at the Kurchatov Institute of Atomic Energy in Moscow. The characteristics of the light reflected and scattered by the plasma were studied during the application of intense nanosecond pulses from a neodymium laser with irradiances of 10^{12}–10^{14} W/cm^2 to plane solid targets.

Certain aspects of these experiments are worth emphasizing:

1) Stimulated Brillouin scattering is studied by a multifaceted systematic approach including measurements of the spectral and space-time characteristics of the scattered light and the properties of the plasma corona.

2) The spectral width of the laser light is narrow, so that the spectra of the stimulated Brillouin scattering can be measured accurately.

3) The plasma corona has a quasi-one-dimensional structure, which facilitates the interpretation of the results.

EXPERIMENTAL APPARATUS AND DIAGNOSTIC FACILITIES

The Mishen'-1 apparatus includes a high-power neodymium-glass laser system, a vacuum interaction chamber, and diagnostic facilities for measuring the properties of the plasma which is produced and the characteristics of the incident light and that scattered by the plasma. The layout is shown in Fig. 1. The laser beam ($\lambda = 1.06\,\mu$m) is focused by a spherical lens with an aperture ratio of 1:3.5 ($f = 170$ mm) onto the surface of plane bulk targets in the vacuum interaction chamber. The average irradiance of the beam at the focus, 50 μm in diameter, ranges up to $2 \cdot 10^{14}$ W/cm^2 at a pulse length of 5 ns. The system for producing the short laser pulse and for optically decoupling the various laser amplifier stages (which use LiF crystals with color centers) provides an energy contrast of 10^5–10^6 for the laser pulse. In the experiments which we will be discussing here, the spectral width of

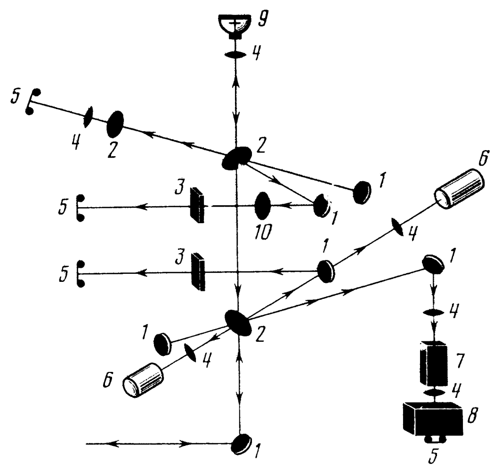

FIG. 1. Arrangement of the diagnostic apparatus on the Mishen'-1. 1—Mirror; 2—beam-splitting wedge; 3—objective, F = 160 cm; 4—lens; 5—camera; 6—calorimeter; 7—spectrograph; 8—image-converter camera; 9—vacuum chamber with target; 10—Fabry-Perot interferometer.

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the laser output line did not exceed 0.1 Å. As targets we used plane disks of $[CH_2]_n$ (polyethylene), Al, and Pb. The energy of the laser light reflected and scattered by the plasma was measured with calorimeters. The spectra were analyzed in the IR region near 1.06 μm with an MDR-2 monochromator (spectral resolution ~0.4 Å) and a Fabry-Perot etalon. The time evolution of the spectra was studied with the help of an Agat SF high-speed image converter at the exit from the spectral instruments.

EXPERIMENTAL RESULTS

Experiments were carried out with the laser beam incident normally and obliquely on the target. Previous measurements[3,4] of the intensity of the emission at the harmonics $2\omega_0$ and $(3/2)\omega_0$ (ω_0 is the frequency of the laser beam) for various angles of incidence of a laser beam on plane targets had demonstrated that the plasma expansion is one-dimensional out to distances at which the electron density falls below a fourth of the critical density for radiation with a wavelength of 1.06 μm. Consequently, when a beam is incident obliquely on the target at an angle exceeding the convergence angle of the rays in the focused beam it becomes possible to spatially separate the specular reflection from the scattering opposite the direction of the incident beam. It is thus possible to separate the broadening of the spectral line of the scattered radiation due to the Doppler effect from that due to the Brillouin instability.

a) Normal incidence

Figure 2 shows the reflection coefficient (R_a) for reflection into the aperture of the focusing lens for normal incidence of the laser beam on targets of $[CH_2]_n$, Al, and Pb versus the beam irradiance in the range 10^{12}–10^{14} W/cm^2. Over the irradiance range studied, the reflection coefficient of targets of a given material changes only insignificantly, while it decreases with increasing atomic number of the target material. The reflection coefficients R_a in the case of $[CH_2]_n$, Al, and Pb targets are 4%, 2%, and 1.5%, respectively. Figure 3 shows the measured time-integrated spectra of the incident beam and of the light scattered into the aperture of the focusing lens for these targets at an irradiance of $5 \cdot 10^{13}$ W/cm^2. The scattering spectra characteristically exhibit a symmetric broadening with respect to the peak of the

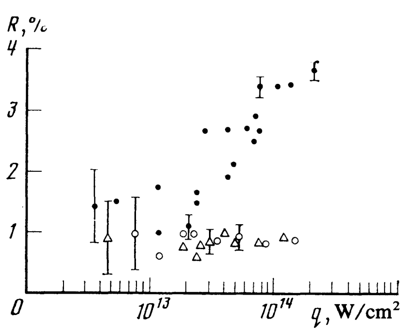

FIG. 2. Reflection coefficients versus the irradiance of the light beam for normal incidence of the laser beam on plane targets. ●—$[CH_2]_n$ target; ○—Al; △—Pb (the pulse length is 5 ns, and the focus diameter is 50 μm).

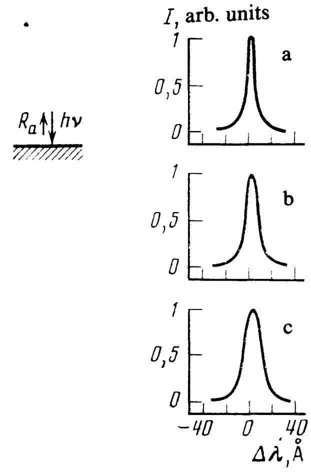

FIG. 3. Time-integrated spectra of the incident light and of the light scattered into the aperture of the focusing lens for normal incidence of the laser beam on targets of Pb (a), Al (b), and $[CH_2]_n$ (c). The irradiance of the light beam at the target surface is $5 \cdot 10^{13}$ W/cm^2.

spectral distribution and also a 2–5–Å shift of the peak toward the long-wave side of the line of the incident laser beam. The spectral width of the scattered light is 2–5 Å for the Pb targets and reaches 10–20 Å for the Al and $[CH_2]_n$ targets.

b) Oblique incidence

Figure 4 shows the arrangement used in measuring the energy and spectral characteristics of the light scattered by the plasma for a laser beam having an angle of incidence of 45° on the target. Both the specular reflection and the scattering opposite the incident beam, into the aperture of the focusing lens, are measured. The results show that the reflection is mostly specular, and the specular reflection coefficient R_{spec} is 1–4%, depending on the target material. In addition to this specular reflection, however, we find a highly directional scattering into the aperture of the focusing

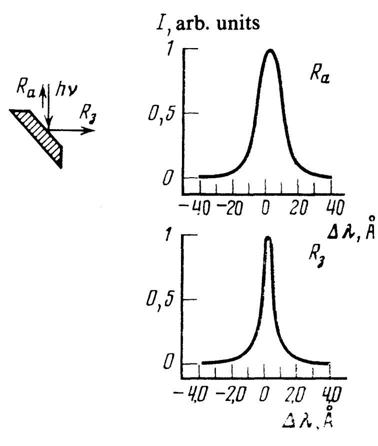

FIG. 4. Spectra of the light scattered by the plasma in experiments with a laser beam incident obliquely on the surface of a $[CH_2]_n$ target. $q = 5 \cdot 10^{13}$ W/cm^2.

lens. For the $[CH_2]_n$ target at an irradiance of 10^{13} W/cm^2, the fraction of the light scattered into the aperture of the focusing lens [the coefficient $R_a(45°)$] reaches 1%, and the spectral line broadens to 15 Å. In the case of the Pb target, the intensity of the light scattered into the aperture of the focusing lens under the same conditions is at the sensitivity limit of the measurement apparatus, and $R_a(45°)$ cannot be determined accurately (the width of the spectral line is at most 0.5 Å).

In all cases, the spectral width of the specular reflection is about 0.5 Å. The spectral broadening detected in the scattered light in the case in which the laser beam is incident normally on the target has usually been interpreted (Ref. 5, for example) as resulting from the Doppler effect in the inhomogeneously expanding plasma. The narrow line of the specular reflection in the present experiments is evidence that the Doppler mechanism makes an insignificant contribution to the observed spectral width of the light scattered into the aperture of the focusing lens; the broadening is instead due primarily to the onset of nonlinear processes. Since these nonlinear processes occur only after a threshold intensity is reached, we carried out a special series of experiments to measure the scattering spectra for various beam irradiances at a fixed focal size.

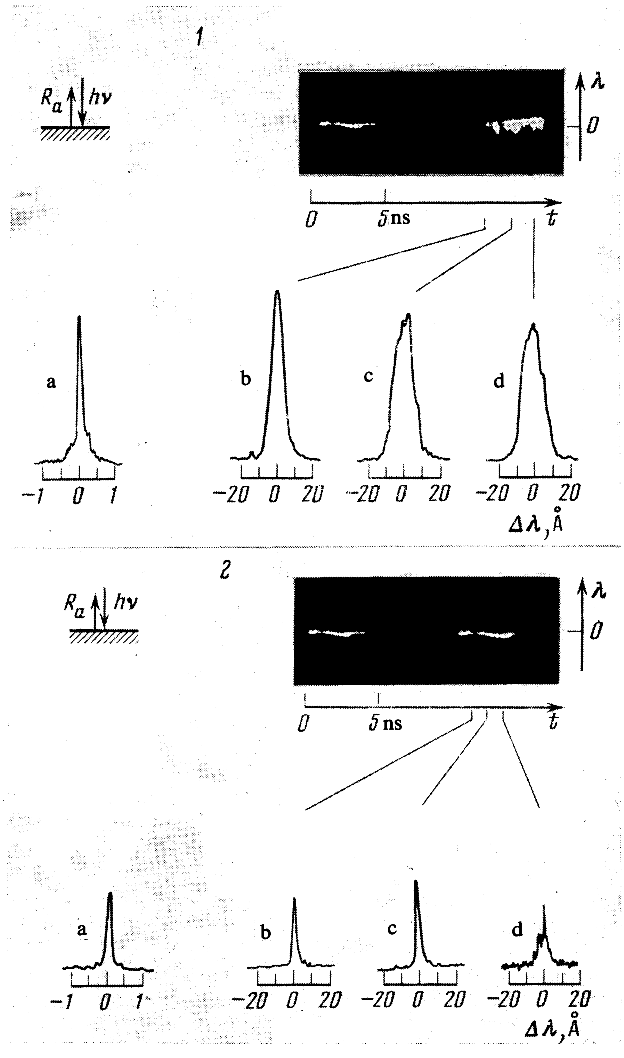

FIG. 5. Time sweeps of the spectra of the incident light and of the light scattered into the aperture of the focusing lens for normal incidence of the laser beam on the surface of a $[CH_2]_n$ target. 1—$q_1 = 2 \cdot 10^{14}$ W/cm^2; 2—$q_2 = 10^{12}$ W/cm^2. a) Densitometer trace of the spectrum of the incident light; b–d) densitometer traces of the spectrum of the scattered light at various times.

Figure 5 shows time sweeps of the spectra of the incident laser beam and of the light reflected from a $[CH_2]_n$ plasma in experiments in which the laser beam was incident normally on the target surface, at various irradiances. At $q_1 = 2 \cdot 10^{14}$ W/cm^2 the spectrum of the light scattered into the aperture of the focusing lens is significantly broadened ($\Delta\lambda \approx 15$ Å) from essentially the very beginning of the laser pulse, and we observe a modulation of the intensity of the scattered light with time. At $q_2 = 10^{12}$ W/cm^2, on the other hand, there is no significant spectral broadening: $\Delta\lambda \sim 0.5$–1 Å. At intermediate values of q_3 ($q_2 < q_3 < q_1$) broadens symmetrically as the intensity rises. These results indicate that the processes responsible for the spectral broadening are "hard."

DISCUSSION OF RESULTS

The measurements of the reflection coefficient R_a with the laser beam incident normally on the surface of the samples demonstrates the strong absorption ($\geqslant 90\%$) of the plasma in the range of beam irradiances studied. The increase in the absorption by the plasma with increasing atomic number of the target material (from $[CH_2]_n$ to Pb) agrees with the interpretation that the classical collisional mechanism for absorption is highly effective. In experiments with the laser beam incident obliquely on the $[CH_2]_n$ target we observed a highly directional scattering into the aperture of the focusing lens, containing $\sim 1\%$ of the energy of the incident laser beam. In some earlier measurements[3,4] this fraction was at most 10^{-3}–10^{-4}. The only distinctive feature of the present experiments was the narrow spectral line, ~ 0.1 Å, in comparison with a spectral width of 40–50 Å for the laser beam in Ref. 3. We know[6,7] that if the spectral width along the frequency scale, $\Delta\omega$, exceeds the growth rate of the instability for the case of monochromatic light, γ_0, then the growth rate of the waves will decrease by a factor of $\Delta\omega/\gamma_0$, and the instability thresholds will rise accordingly. At a beam irradiance $\sim 10^{13}$ W/cm^2 and a spectral width ~ 50 Å of the incident light, we would have $\gamma_0/\Delta\omega \sim 10^{-1}$, so that the experimental results reported in Ref. 3 can be explained in a natural way.

Stimulated Brillouin scattering in the interaction of a laser beam with a plasma has usually been interpreted on the basis of the following simple model: The incident electromagnetic wave **t** decays in the plasma into a sound wave **s** and a scattered electromagnetic wave **t**′(**t** → **t**′ + **s**). This approach is valid as long as the growth rate of the stimulated Brillouin scattering,

$$\gamma_0 = [\omega_0 \omega_{pi} / (2\omega_0 \omega_s)^{1/2}] (E_0^2 / 8\pi mnc^2)^{1/2},$$

is lower than the ion acoustic frequency ω_s. The ion acoustic frequency can be written as $\omega_s = \omega_{pi}(k_s r_D)$, where $\omega_{pi} = (4\pi n e^2 Z/M_i)^{1/2}$ is the ion plasma frequency, n is the electron density, Z is the ion charge, M_i is the ion mass, k_s is the wave number of the sound wave, and r_D is the Debye length.

Since the relation $k_s = 2k_0 = 2\omega_0/c$ holds for backscattering, opposite the direction of the incident laser beam (k_0 is the wave number of the incident light wave, and c is the velocity of light in vacuum), the value of the frequency ω_s estimated for typical plasma properties ($T_e \approx 0.5$ keV, $n \approx 10^{21}$ cm, $Z = 6$–10) is $\omega_s = 7 \cdot 10^{11}\ \mathrm{s}^{-1}$. The spectrum of the scattered light is shifted downward along the frequency scale by an amount equal to the sound frequency, ω_s (a "red shift"). At the same time, as we have already mentioned, a Doppler frequency shift of the scattered light should also occur in the moving plasma. In those cases in which the plasma flow velocity becomes supersonic, the frequency of the scattered light may exceed that of the incident light (a "blue shift"). Inhomogeneity in the velocity blurs the spectrum; some extremely detailed studies of this effect have been carried out by Gorbunov and Polyanichev.[5] However, an attempt to explain the spectral width of the scattered light in the present experiments on the basis of the Doppler effect failed, since the corresponding plasma velocities would have to have been unrealistically high, above 10^8 cm/s.

At $\gamma_0 > \omega_s$ the nature of stimulated Brillouin scattering changes substantially: The instability converts into a modified decay instability.[8,9] In this case, also called the strong-coupling approximation,[10] in which the group velocities of the growing waves are higher than or comparable to the sound velocity, we can no longer talk in terms of sound waves, and the scattering is by density fluctuations which are excited by ponderomotive forces. The nature of these fluctuations is determined by the ion inertia, not by the plasma pressure, and it does not depend on the relation between the electron and ion temperatures. The turbulence which arises can be expected to be time-varying. Convincing evidence for this conclusion comes from the results of experiments on the stimulated Brillouin scattering of a CO_2 laser beam in a low-density plasma in which density fluctuations were measured directly.[11] The time variation of the stimulated Brillouin scattering in this regime has also been demonstrated by some numerical calculations.[12] The spectral broadening observed in the present experiments can be linked with the time variation of the turbulence. The spectral broadening of the scattered light is detected beginning at an irradiance of $3 \cdot 10^{12}$ W/cm^2. The ratio γ_0/ω_s here is 0.3, or slightly below the value expected for a transition to the time-varying regime. However, the filamentation of the incident laser beam can lead to local beam irradiance levels substantially higher than the measured threshold values, averaged over the focus. Since the spectral broadening on the frequency scale is substantially greater than the sound frequency, the scattering by time-varying density fluctuations leads to both red and blue shifts. Some of the energy, however, is transferred to sound waves; this transfer explains the overall spectral shift in the long-wave direction observed experimentally.

The scattering length for the modified decay can be estimated from

$$L \sim c/\gamma_{\mathrm{mod}} \sim c/\omega_{pe}(M_i/m)^{1/6}(E_0^2/8\pi n T_e)^{-1/3}(c/v_{Te}).$$

An interesting effect occurs in this region of parameter values: Since the scattered wave grows from the thermal noise level, and the instability is convective, there is significant stimulated Brillouin scattering when the length of the plasma slab is greater by a factor of Λ (or more) than the scattering length (Λ is the logarithm of the ratio of the amplitudes of the incidence wave and the thermal noise). Under realistic conditions we would have $\Lambda \sim 5$–8. For normal incidence of a low-intensity laser beam on a plane slab of inhomogeneous plasma, the wave reflected from the critical-density surface would not affect the stimulated Brillouin scattering. If, on the other hand, the intensity of the laser beam is high, and the condition $\gamma_0 > \omega_s$ holds, the width of the resonance will exceed the difference between the frequencies of the scattered and reflected waves. The reflected wave now serves as a "seed" for the stimulated Brillouin scattering, and the scattering increases sharply. When the motion of the plasma is taken into acount, the required intensities may be lowered because of the compensation for the frequency difference by the Doppler shift.[13] This effect had been discovered in earlier experiments on microwave scattering.[14] Our experiments confirm this qualitative picture. In the experiments with a laser beam incident normally on a $[CH_2]_n$ target, above a threshold beam irradiance ($\sim 10^{13}$ W/cm^2), the intensity of the stimulated Brillouin scattering is about five times that in the case of oblique incident of the laser beam, with the same parameter values. The absence of a narrow line from the spectrum of the light scattered into the aperture of the focusing levns is evidence of efficient pumping of energy from the reflected wave to the scattered wave.

We conclude with a few words about the instability threshold, which may be determined by either the inhomogeneity of the plasma or collisions between particles. The absence of spectral broadening in observations of the scattering in experiments on the bombardment of targets made of elements with high atomic numbers is evidence that collisions play a dominant role under these conditions.

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