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SPECTRAL ANALYSIS OF BACKREFLECTED LIGHT AND HARMONIC GENERATION IN A CO_2 LASER-TARGET INTERACTION EXPERIMENT

C. GARBAN, E. FABRE, C. STENZ, C. POPOVICS, J. VIRMONT and F. AMIRANOFF

Laboratoire de Physique des Milieux Ionisés, Groupe de recherche du C.N.R.S.,
Ecole Polytechnique, 91128 Palaiseau Cedex, France

GRECO, Interaction Laser-Matière,
Ecole Polytechnique, 91128 Palaiseau Cedex, France

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Résumé. — Dans des expériences d'interaction laser CO_2-cible solide, nous avons étudié le spectre de la lumière réfléchie ou réfractée à la fréquence fondamentale du laser ou à ses harmoniques. L'analyse du spectre à la fréquence fondamentale fait apparaître une raie déplacée vers le rouge qui est interprétée comme due à la rétrodiffusion Brillouin stimulée et qui correspond à une faible fraction de la lumière rétrodiffusée. Les harmoniques 2ω et $3/2\omega$ ainsi que leurs spectres ont été observés ; leur génération montre la présence d'instabilités paramétriques telles que la décomposition paramétrique ou l'instabilité deux plasmons dans l'interaction laser-plasma. Les harmoniques permettent de plus, d'accéder à la mesure locale de certains paramètres du plasma, tels que la température électronique et la grandeur caractéristique du gradient de densité.

Abstract. — We have studied the spectrum of the light reflected or refracted at the fundamental laser frequency and its harmonics in CO_2 laser-target interaction experiments. At the fundamental frequency the spectrum shows a red component which is interpreted as due to Brillouin backscattering ; it represents only a small fraction of the backscattered light. The harmonics 2ω and $3/2\omega$ have been observed and their spectrum investigated. The origin of these harmonics is interpreted in term of instabilities, such as the parametric decay and the 2 plasmons instability, in laser-plasma interaction. These harmonics permit us, to determine the local electron temperature and density scale length.

1. **Introduction.** — Spectral analysis of reflected or backscattered light in target interaction experiments with a neodymium laser [1-4] and more recently with a CO_2 laser [5-9], has shown evidence of stimulated Brillouin backscattering and also the occurrence of several harmonics of the incident laser frequency.

These results have permitted the determination of some macroscopic plasma parameters, such as the focal spot diameter or the electron density scale length [10-12]. Of even greater interest is the insight into the interaction processes of intense laser light with plasma which is provided by such measurements.

We present here recent experimental results obtained in the case of the interaction of a CO_2 laser with a solid target, which are related to the observation of harmonics and the information which they carry concerning the laser-plasma interaction.

2. **Experimental set-up** (Fig. 1). — The output beam of a CO_2 laser which provides 40 J in 40 ns (F.W.H.M.) pulses is focused onto a plane polyethylene target by means of a 20 cm, $f/2.5$ aperture parabolic mirror. The maximum flux onto the target is 10^{12} W/cm^2. The focal spot diameter (250 ± 20) μ was determined by two independent methods, namely from laser burn patterns on thermosensitive paper, as well as from the 2ω emission as a function of the focal spot position relative to the target.

Flux variations were obtained by attenuation of the beam with thin plastic foils.

The diagnostics set-up for this experiment were the following :

— Optical energy balance with photon-drag detectors ;

— Spectroscopic analysis of the light with an

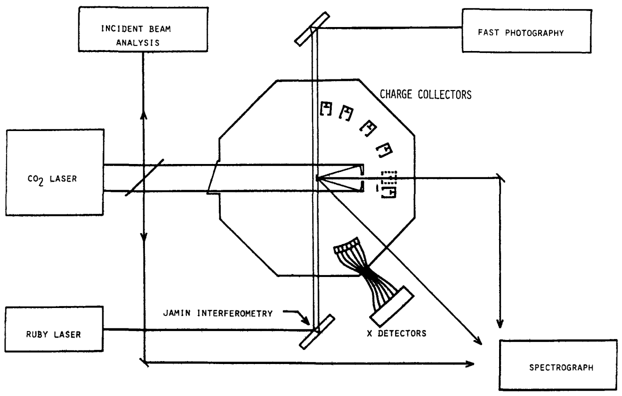

FIG. 1. — Schematic diagram of experimental set-up.

infra-red monochromater from Sopra, which has a resolution of 3.5 Å at 10.6 μ ;

— Light detection at the fundamental frequency and its harmonics with high-sensitivity, fast rise time, HgTe-CdTe photovoltaic detectors from SAT ;

— Electron temperature was measured from the continuum X-ray emission by the absorber foil method [13] ;

— Other diagnostics, as Jamin interferometry and Schlieren photography have provided measurements of the electron density distribution and scale length [14].

3. **Experimental results.** — 3.1 BACKSCATTERED LIGHT AT ω_0. — The spectra of the backscattered light at the fundamental frequency in the aperture of the collimating optics and at 30° from the laser axis are shown in figure 2.

The spectra are strongly broadened. The half-width is (50 ± 10) Å for an incident flux of 10^{12} W/cm^2 at 0°. This broadening is less significant at 30° and 45°. The peak intensity in the spectrum is obtained at the original fundamental frequency.

One can distinctly observe however, a strong asymmetry toward the red for a laser intensity above 10^{11} W/cm^2, which in some cases appears as a distinguishable red-shifted component. The fraction of laser light in the red shifted component is only 25 % of the light reflected in the collimating optics or 2 % of the total incident laser light. The maximum measured red shift is 40 Å.

These results are interpreted as the evidence of stimulated Brillouin backscattering [15-18] which is well known to give rise to a red shifted component.

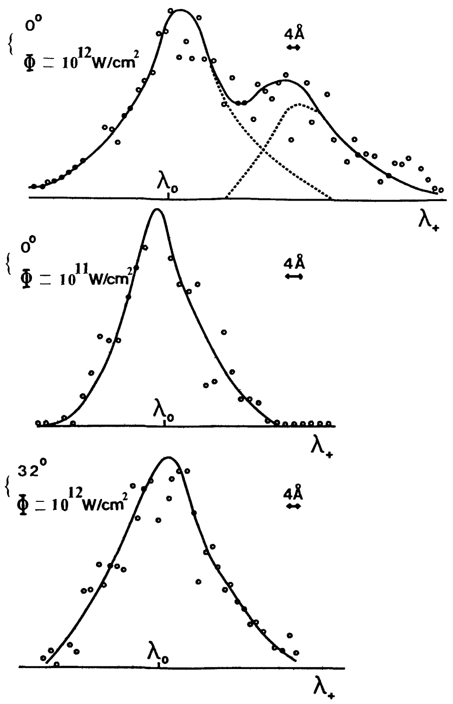

FIG. 2. — Spectrum of backreflected light at $\Phi = 10^{12}$ W/cm^2 and $\Phi = 10^{11}$ W/cm^2 at 0° ; $\Phi = 10^{12}$ W/cm^2 at 32°.

The red shift is equal to the frequency ω_i of the ion-acoustic wave excited in the process :

$$\Delta\omega = \omega_i \simeq 2\,k_0\,c_s = 2\,k_0\,\sqrt{\frac{ZkT_e}{m_i^*}}$$

where k_0 is the wave vector of the incident beam, T_e is the electron temperature, Z and m_i^* are the effective charge of the ions in the plasma.

The experimental value of the red shift has been compared with the theoretical determination using for the temperature values obtained from X-ray emission [13]. Table I gives this comparison.

Some descrepency is found at first. If we take into account, however, the effect of the refractive index of the plasma near the critical density, then a fairly good agreement is found between theoretical and experimental results showing that the instability takes place in a region where $n_e = 0.85\,n_c$.

The spectrum was also analysed at the fundamental frequency in directions which make an angle with the incident laser light. In this case, the spectrum of the scattered light was still broadened but symmetrical, which confirmed that the red shifted component is the result of the Brillouin backscattering in stability.

TABLE I

Φ W/cm^2	10^{12}	6.7×10^{11}	4.4×10^{11}	3×10^{11}	2×10^{11}	1.3×10^{11}	9×10^{10}
T_e (eV)	300	260	230	200	170	150	130
$\Delta\lambda$ (Å) experimental	36	31	30	26	24	18	19
$\Delta\lambda$ (Å) theoretical	85	78	73	68	64	60	55
$\Delta\lambda$ (Å) $n_e = 0.85\,n_c$	33	30	28	26	25	23	21

3.2 HARMONICS OF LASER LIGHT. — Several harmonics of the fundamental frequency have been evidenced at 3 ω, 2 ω and 3/2 ω [5]. Their efficiency conversions are respectively 2×10^{-8}, 5×10^{-6} and 10^{-8} of the incident laser light.

3.2.1 2 ω *emission.* — Figure 3 shows a typical spectrum of the second harmonic integrated in time. Two components are clearly observed. The first one is centred at 2 ω and is the dominating contribution at low intensity. The second one is red shifted and is the dominant contribution at high intensity.

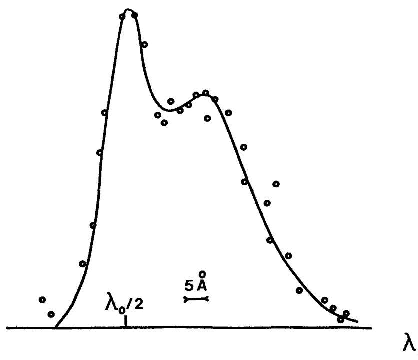

FIG. 3. — Spectrum of the second harmonic integrated in time.

Those results show that two processes may occur in the generation of the second harmonic.

The unshifted component is attributed to the classical second harmonic generation at oblique incidence in electron density gradient [19]. Its intensity variations with laser flux Φ is clearly Φ^2.

The red shifted component can be attributed to the coalescence of a photon and a plasmon parametrically excited, as suggested by the theory of Silin [20] of parametric resonance. The frequency shift corresponds then to the frequency of the phonon emitted near critical layer during the process, as given by the theory of Silin :

$$\Delta\omega = \sqrt{3}\,\omega_{\mathrm{Li}}\left(\frac{v_{\mathrm{Te}}^2}{c^2} + \frac{1}{4}\frac{v_0^2}{c^2}\frac{\omega_0}{\Delta\omega_0(x)}\right)^{1/2}$$

where ω_{Li} is the ion Langmuir frequency, v_{Te} is the electron thermal speed, v_0 the oscillating velocity of electron in the field of the incident wave, x the distance between the resonant and the critical layer, and

$$\Delta\omega_0(x) = \omega_0 - \omega_{\mathrm{p}}(x) = \omega_0\frac{x}{2L} = \frac{1}{2}\omega_0\left(\frac{c}{L\omega_0}\right)^{2/3}.$$

For a plasma of polyethylene created by a CO$_2$ laser, the red shift can be expressed as follows :

$$\Delta\omega_0 = 2.3 \times 10^{-2}\,\omega_0 \times$$
$$\times\,(2 \times 10^{-6}\,T_{\mathrm{e}} + 1.47 \times 10^{-17}\,L^{2/3}\,\Phi)^{1/2}$$

where T_{e} is in eV, L in μ and Φ in W/cm^2.

For $\Phi = 10^{12}$ W/cm^2, $T_{\mathrm{e}} = 300$ eV and $L = 300$ μ, the computed value is 22 Å, and for

$$\Phi = 2 \times 10^{11}\ \mathrm{W/cm^2}\,,$$
$$T_{\mathrm{e}} = 175\ \mathrm{eV}\quad \text{and}\ L = 150\ \mu\,,$$

it is 15 Å.

This is in good agreement with the experimental determinations which are respectively (23 ± 2) Å and (13 ± 2) Å.

This red shift can be used as a determination of the electron temperature at low intensity, when the first term in the bracket is dominant. For intensity below 10^{11} W/cm^2, this is the case and the shift must be proportionnal to the square root of the electron temperature.

3.2.2 3/2 ω *emission.* — The intensity of the 3/2 ω which is 10^{-8} of the incident laser light, is much smaller than it has been observed in Neodymium experiments [2-4]. This harmonic appears above a threshold (Fig. 4) which is estimated between 1-2 × 10^{11} W/cm^2, and seems to show a saturation above 6×10^{11} W/cm^2. A typical spectrum observed at 30° from the laser incident axis is shown on figure 5. Two components are clearly observed. A narrow component (35 Å F.W.H.M.) with a 35 Å blue-shift, and a broader component (150 Å F.W.H.M.) with a (80 ± 10 Å)

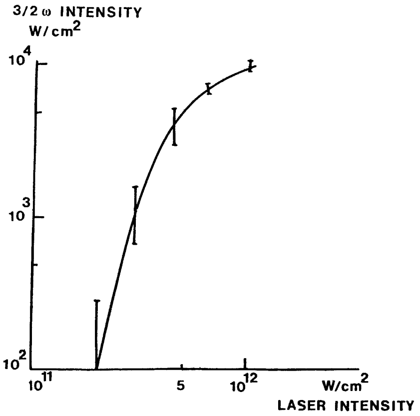

FIG. 4. — 3/2 ω intensity variation *versus* laser intensity.

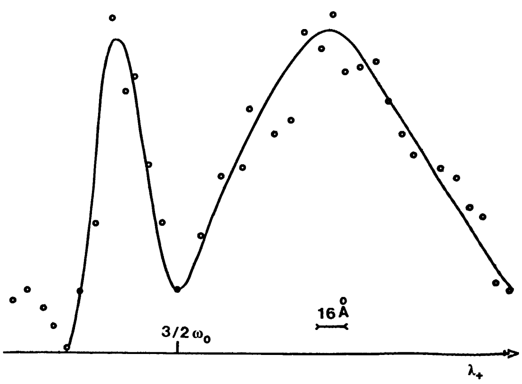

Fig. 5. — 3/2 ω spectrum.

red shift. The minimum of intensity is observed at the unperturbed frequency $3/2\ \omega_0$. The intensity ratio between the red and the blue component is about 3-4.

It is well known that the generation of the $3/2\ \omega$ is correlated to the onset of the 2 plasmon-instability which generates two plasmons at $\omega/2$ and which occurs near quarter critical density [21]. The threshold for this instability, detected from the intensity variation of the $3/2\ \omega$, is in good agreement with the theoretical prediction for an inhomogeneous plasma [22], for an electron temperature $T_e = 170$ eV and a density scale length $L = 100\ \mu$.

For the generation of $3/2\ \omega$, two mechanisms can then presumably contribute [23] :

— the interaction of an incident photon and a parametrically excited plasmon ;

— three plasmons interaction.

The second mechanism is a non linear process of higher order compared to the first one, but can have an equivalent efficiency because of the difficulty in obtaining the matching condition on the wave vectors for the first process. A. Avrov *et al.* [23] give an expression for the conversion efficiency of $3/2\ \omega$ by these two processes :

$$I_{3/2} = 2.3 \times 10^{-17} I_0^{3/2} T_e^{3/2} A \frac{L}{\lambda_0}\left(1 - \frac{1}{p}\right)^2 \left(1 + 1.4 \times 10^6 \frac{\lambda_0 T_e^2}{ZL}\right)^{-1/2} \times$$
$$\times \left[1 + 78.3\, T_e^4 \frac{A^2}{Z^3}\left(1 - \frac{1}{p}\right)^4 \left(1 + 1.4 \times 10^6 \frac{\lambda_0 T_e^2}{ZL}\right)^{-1}\right] \qquad (1)$$

where $I_{3/2}$ and I_0 are the intensities in W/cm^2, T_e is in keV, λ_0, the incident wavelength and L, the density gradient scale length at $n_c/4$, in cm, A and Z are the atomic weight and the charge of the ion and

$$p^2 = \frac{I_0}{I_{\text{threshold}}}\,.$$

The expression in the bracket represents the relative contribution of the two processes.

The theory predicts a spectrum with two components symmetrically shifted by

$$\Delta\omega = 4.7 \times 10^{-3}\, T_e\, \omega_0 \cos\theta \qquad (2)$$

with respect to the harmonic frequency $3/2\ \omega$.

θ is the angle between the laser axis and the direction of harmonic emission.

As mentioned in this paper, the red shifted component is emitted in the direction of observation and the blue shifted component is emitted towards the high density region and reflected at its critical density layer $9\, n_c/4$ where it is partially absorbed. This could explain the intensity difference between the two components, and why in the experiment of Offenberger [24] in subcritical plasma, only the red shifted component is observed.

From the expression (2), the electron temperature can be determined. Because of the Doppler effect, some asymmetry appears in the spectrum. The exact value of the shift must then be taken as the half of the frequency difference between the two components. For a frequency shift of $(35 + 80)/2$ Å, using the reduced formula :

$$T_e = 4.9 \times 10^2 \frac{1}{\cos\theta}\left(\frac{\delta\lambda}{\lambda_0}\right)$$

obtained from [2] to determine the electron temperature, we obtain $T_e = 0.3$ keV in good agreement with the determination by the X-ray emission in the continuum.

The formula (1) gives the efficiency of $3/2\ \omega$ production as a function of electron temperature and density scale length at quarter critical density. In our present experiment, however, the agreement is not very good and the experimental value is 100 times larger than the theoretical one.

4. **Conclusion.** — In our experiment, we have shown evidence for the generation of $2\ \omega$ and $3/2\ \omega$ harmonics, and also Brillouin backscattering during the interaction of a CO$_2$ laser with a massive target. It appears that Brillouin backscattering is only a small fraction of the reflected light, the major part of the losses being due to refraction. The analysis of the harmonics and their spectrum evidenced the onset of parametric instabilities during interaction, but their conversion efficiency is small and they may not contribute significantly to the absorption of the laser light in our experimental conditions.

Harmonic generation has been also used as suggested by O. Krokhin *et al.* [20] to obtain the electron temperature determination and also some estimate of the value of the electron density scale length in the region where the instabilities take place. These techniques appear to be very useful as a diagnostic tool of interaction mechanisms and for the determination of plasma parameters. However, when the electron density scale length is very small and comparable to the laser wavelength, the preceeding theory cannot be applied [25].

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