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Resonance absorption in CO₂ laser-plane targets interaction experiments

C. Garban-Labaune, E. Fabre, F. David, J. Maignan and A. Michard

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. — Nous avons étudié l'influence de la polarisation et de l'angle d'incidence sur l'absorption du rayonnement d'un laser à CO₂ (12 J-1 ns) en interaction avec des cibles planes de polyester pour des flux de 5×10^{11} - 5×10^{12} W/cm². Les mesures d'absorption sont obtenues à partir de la mesure intégrale de la réflexion à 10,6 μm dans une sphère d'Ulbricht. Les résultats montrent clairement la présence de l'absorption résonnante par un maximum d'absorption en polarisation *p* pour des angles d'incidence ~ 20 - 27° , conformément au modèle théorique classique ; cependant, ce mécanisme ne suffit pas à expliquer les taux d'absorption en incidence normale, et ne rend pas compte exactement des variations angulaires observées. Un modèle simple faisant intervenir les modulations de densité à la surface critique, ainsi que le champ magnétique, donne une interprétation plausible des phénomènes observés.

Abstract. — We have studied the polarization and angular dependence of the absorption of a CO₂ laser (12 J-1 ns) by polyester plane targets at fluxes of 5×10^{11} to 5×10^{12} W/cm². The fraction of absorption are obtained from the measurement of the entire reflexion at 10.6 μm in an Ulbricht sphere. The results clearly show the presence of resonance absorption by a maximum of the absorption of *p* polarized light for angle of incidence of 20 - 27° , as predicted by classical theory ; however this mechanism is not sufficient to explain the values of absorption observed at normal incidence and predict a more important angular dependence of the absorption compared to the observation. A simple model including density modulations at the critical surface and magnetic field gives a good interpretation of the observed phenomena.

1. Introduction. — The study of the light absorption mechanisms is of great importance in laser-plasma interaction experiments and many theoretical and experimental works have been done which can explain the special experimental situations. Different processes have been suggested to explain the absorption of laser light in plasma as Inverse Bremsstrahlung [1, 2], resonance absorption [3-7], parametric instabilities [8], and ionic turbulence [9, 10]. However the occurrence and the efficiency of those mechanisms depends strongly upon experimental conditions as light intensity, laser pulse duration and wavelength.

At low intensities on target, Inverse Bremsstrahlung can be a very efficient process. Strong absorption explained by this mechanism has been observed in different experimental conditions [11, 12], showing that shorter wavelengths (0.53 μm-0.26 μm) and long pulses (~ 1 ns) were favourable for efficiency of I.B., when losses due to Stimulated Brillouin were unimpor-

tant. For long wavelength (10.6 μm), for irradiance above 10^{10} W/cm² the efficiency of I.B. could be a problem even if there are no Brillouin losses.

Indeed the corona temperature can be high enough to reduce I.B. absorption when the electron density scale length is small. This situation occurs for short pulses (< 1 ns) or at high intensities, when some electron density profile modification due to radiation pressure is produced. However it is observed in many experiments that absorption level of 30 % to 40 % are still obtained even at high fluxes [13-16]. Under these experimental conditions the most likely processes to explain this absorption efficiency are the non collisional mechanisms.

Parametric instabilities have been observed as electron-ion decay [17] and two plasmons [18], but there efficiency is not yet determined. Moreover at very high intensities, profile modification is not in favour for the onset of instabilities. On the other hand resonance

absorption will find favourable conditions under those circumstances. This process has been evidenced in Neodymium experiments and short pulses [13-16].

For CO₂ experiments there are less experimental data concerning this observation and the data are mostly upon the plasma parameters variations with angles of incidence [19, 20] rather than absorption efficiency.

We present here some experimental results in which the study of total absorption dependence with angle of incidence on target and also with laser polarization clearly demonstrate the occurrence of resonance absorption in plane target irradiation at intensities in the range of 5×10^{12} W/cm².

2. Experimental set-up (fig. 1). — We used a CO₂ laser beam with an actively mode locked oscillator which can deliver one pulse of 6 mJ in 1 ns (F.W.H.M.). This pulse is amplified by multiple passes through preionized, atmospheric pressure CO₂ amplifier units. The final pulse has a maximum energy of 12 J, with a rise time of 500 ps and a decay time of 1.5 ns. The pulse shape is controlled on each shot with an oscilloscope Tektronix R 7912 which permits us to detect a level of prepulse of 100 μ V compared to the main pulse of ~ 10 V. A saturable absorber cell of SF₆-He gives a contrast ratio of $\sim 10^5$. The polarization of the output beam is 97 % in the horizontal plane which correspond to the *p*-polarization. The change from *p* to *s*-polarization is made by metallic reflexion which introduces a small depolarization.

Fig. 1. — Schematic diagram of the experimental set-up.

The laser is focused onto plane polyester targets by means of a long focal length (120 cm) spherical mirror with *f*/12 aperture; this system gives a very good definition of the angles of incidence on the target, within 3° which correspond to the half angle of the cone in which the laser beam is focused. The focal spot diameter is (400 ± 100) μ m and the maximum flux

on the target is 5×10^{12} W/cm². Some experiments have also been done at lower fluxes; flux variations on the target are obtained by attenuation of the beam with plastic foils, but this can introduce some depolarization of the beam.

The major diagnostic in this experiment is the optical energy balance by means of an Ulbricht sphere [21-14] which is shown on the figure 1. The light reflected by the target is scattered on the grounded surface of the sphere and three pyroelectric detectors from Gen-Tec, protected from the direct light, provide a measurement of the light energy in the sphere which is proportional to the reflected light. The average of these three values gives a measurement of the fraction of all the reflected light except in the optic of collimation; this last measurement is made on an other calorimeter outside of the vacuum chamber. All the reflected light is then measured and we deduced from it the total absorption.

This device permits us to study the effect of the angle of incidence on the target and of the polarization of the laser on the absorption measurements.

3. Experimental results. — In figure 2, we present the variations of absorption in different experimental

Fig. 2. — Absorption of *p* and *s* polarized light versus angle of incidence at a flux of 5×10^{12} W/cm² on plane polyester targets.

conditions which correspond to the average over 5 series of shots. The first curve corresponds to the case where the polarization is in the *p* condition which is defined as the electric field of the incident wave in the plane of incidence. The intensity in this experiment is 5×10^{12} W/cm². At normal incidence the absorption is (30 ± 5) %; when increasing the angle of incidence, at first absorption maintains at a large level and even increases and reaches a maximum value of 35 % for an incidence of about 25°. Absorption maintains to a level of 30 % up to 40°-45° of incidence.

The second curve is the dependency of absorption level in the case of *s* polarization for which the electric field vector is normal to the plane of incidence. There is a clear difference with the previous case for the

absorption efficiency behaviour with incidence, demonstrating the role played by resonance absorption which is expected from the classical theory for the p polarization. Something which is also interesting in this curve is the level of absorption around 40-45° which seems to be rather large for this incidence both for s and p polarizations.

The second point to be mentioned is that the level of absorption at normal incidence is much larger than expected from classical resonance absorption. This was first observed in Neodymium experiments [13] and suggested as the evidence of rippling at critical surface or magnetic field to explain this absorption. In the last part of this paper we will present some numerical results of resonance absorption in the presence of rippling at critical surface and magnetic field which could explain our experimental results.

The optical energy balance has shown that most of the losses are due to refraction and detected in the sphere. Only a very small fraction of the incident light is backreflected in the optic of collimation, about 1 % of backreflection is measured at normal incidence and less than 0.5 % at non normal incidence. This is evidence of very poor efficiency of Stimulated Brillouin Scattering in the present experimental conditions. This conclusion was already stated by other authors and is clearly seen in the CO₂ experiments from Los Alamos at higher intensities.

4. Discussion of the results. — As we have seen previously the classical model of resonance absorption in a linear density gradient [3] cannot explain entirely the experimental results that we have obtained and some other mechanisms have to be considered.

First the contribution of Inverse Bremsstrahlung may be estimated by using the gradient scale length L determined from the angle of optimum absorption in p polarization :

$$(K_0 L)^{1/3} \sin(25^\circ) = 0.8 \quad \text{gives} \quad L = 10 - 20 \mu\text{m}.$$

The temperature is estimated by the velocity distribution of the ions emitted from the plasma and is of the order of 230 eV. The I.B. absorption A at normal incidence is then estimated to :

$$A = 1 - \exp - \left(7.64 \frac{L(\mu\text{m})}{T_e^{3/2}(\text{eV})} \right) \leq 5\%.$$

So, the contribution of I.B. is not important ; this is confirmed by the absorption measurement at lower flux ($5 \times 10^{11} \text{ W/cm}^2$) which leads to the same values than at $5 \times 10^{12} \text{ W/cm}^2$.

Secondly, as suggested by J. J. Thomson *et al.* [22] resonance absorption may be present even at normal incidence. Indeed the non planarity of the expansion and the possible existence of ripples or cavities at critical surface modify the propagation of laser light in the corona, and lead to an effective incidence of light which is non zero, even at normal incidence. This

mechanism could be a possible explanation of the absorption efficiencies observed in our experimental conditions. Indeed we made a comparison of our experimental data with the results of computations performed with the 2-dimensional model developed by R. Pellat and one of us [24], in order to estimate the importance of such a process. This model allows us to compute the resonance absorption of a p -polarized wave in a 2-dimensional rippled density profile (the wave vector of the ripple being in the plane of incidence) and takes into account the full propagation of the wave in the corona. This model being 2-dimensional does not take into account the case of rippling out of the plane of incidence (this case shall be discussed later but should not modify qualitatively the results for the p -polarization). The results are shown of figure 3 for conditions corresponding to our experimental case (the details of the computations are given in reference [24]).

Fig. 3. — Computed resonance absorption of a p wave on a rippled surface as a function of the angle of incidence for different values of the maximum slope of the ripples α . The wave vector of the ripples is in the plane of incidence and the wavelength of the ripples are taken to $10 \mu\text{m}$.

The gradient scale length L and the ripple wavelength l are taken of the order of $10 \mu\text{m}$ (such an order of magnitude is expected for l , whatever the mechanism of ripples formation could be : Rayleigh Taylor or electromagnetic instability). The main parameter is then the maximal slope of the ripples α , which corresponds to the maximal effective incidence of light at the critical surface. We give on figure 3 the computed absorption of a p wave as a function of the incidence for different values of α . There seems to be a relatively good agreement with experimental results for a α value of 20° which gives 25 % of resonance absorption at normal incidence. The results of reference [23] in an elliptic plasma are quite similar.

As previously noted, the rippling may also take place out of the plane of incidence, so that s and p waves are mixed, and resonance absorption takes

place also for the s polarization. This effect is not taken into account by the previous model but may be roughly estimated by averaging over the effective angles of incidence as in reference [22]. The absorption curve for the p wave is not too much modified and the absorption coefficient for the s polarization will be maximum at normal incidence (and equal to the absorption of the p wave) and will decrease as the incidence increases, as the experimental results. In fact, the full 3-dimensional geometry of the plasma has to be considered for a more precise estimation and comparison with experimental data. Particularly, the absorption at very high angle of incidence ($\sim 10\%$), independent of polarization, is not well explained.

The existence of D.C. magnetic field of the order of megagauss can also cause resonance absorption at normal incidence [25]. Such toroidal fields are expected in plane target experiments, and may be generated by $\nabla n \times \nabla T$ mechanism or by toroidal return currents around the target [26]. Figure 4 shows the influence of

Fig. 4. — Computed resonance absorption of a p wave in a magnetized plasma. The magnetic field is perpendicular to the incidence plane. The absorption is averaged over the two directions of the field. The gradient length is taken to $10\ \mu\text{m}$.

such an effect on a p polarized wave. The absorption is computed for a magnetic field perpendicular to the incidence plane, and is averaged over the two directions of the field (the gradient length is taken to $10\ \mu\text{m}$). With this simple model we obtain also a significant absorption at normal incidence for a magnetic field less than 1 megagauss but the maximum of absorption

is still pronounced; so if this mechanism is present, it should be mixed with the previous one.

Finally we see that we can reproduce the experimental results for incidence angle $\leq 40^\circ$ by taking into account the non planarity of the plasma and eventually the existence of magnetic field.

However, there is no experimental evidence that those mechanisms are the only one which are present in this experiment and other processes may occur. For example, soliton formation [27], self generated magnetic field [28-29] or ponderomotive force may modify the resonance absorption itself. Some experiment [30] also indicate that ionic turbulence should enhance absorption, but its effect is difficult to estimate. Two plasmons instability may also contribute, but probably at a low level.

5. Conclusion. — The results presented in this paper are an evidence of the effect of resonance absorption in CO_2 laser produced plasma experiment. It is very interesting to note that the results, and especially the behaviour at low and high angles, are very similar to those obtained with a Neodymium laser [13], with some differences in the experimental conditions, and a value of $I\lambda^2$ which is approximately the same within a factor 2.

We have shown by computer simulations that resonance absorption with ripples at the critical density surface and magnetic field, can give a good interpretation of the experimental results and particularly for the absorption at normal incidence. This agreement must not exclude the occurrence of other mechanisms depending very few on the angle of incidence and on the polarization.

Moreover, in this experiment, the estimation of the density gradient scale length from the optimum angle of absorption probably shows density profile steepening due to radiation pressure, although the flux is low.

Finally, we have seen that Brillouin instability does not take place in this experiment, level of backscattering being always very low.

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