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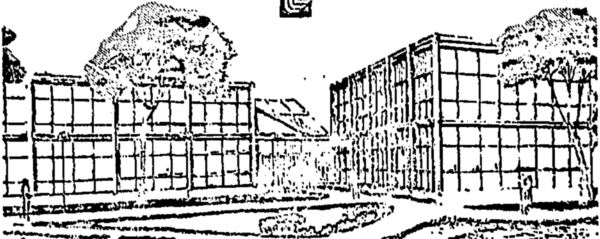

LIGHT ABSORPTION AND SCATTERING
MECHANISMS IN LASER FUSION PLASMAS*

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ABSTRACT

Simulations show resonance absorption occurring on a steepened and rippled critical surface. Stimulated scattering may be present for long laser pulses, and in reactor target chambers.

In this paper we describe the picture of laser light absorption and scattering which is emerging from our theory and computer simulation studies of laser-plasma interactions. On the subject of absorption, we discuss theoretical and experimental evidence that resonance absorption in a steepened density profile is a dominant absorption mechanism. Recent work also indicates the presence of critical surface ripples, which we study using two and three dimensional computer simulations. Predictions of hot electron spectra due to resonance absorption are described, as are effects of plasma outflow. We then discuss two regimes where stimulated scattering may occur. Brillouin scattering is expected in the underdense target blow-off, for long laser pulses, and is limited by ion heating. Raman scattering in the background gas of a reactor target chamber is predicted to be at most a 10% effect for 1 μm lasers.

I. ABSORPTION

An experiment was recently performed at Livermore[1] to test the angle and polarization dependence of absorption for laser intensities $I_L = 10^{15} - 10^{16}$ W/cm^2. We have analyzed this experiment theoretically, using computer simulations of resonance absorption.[2] Since the light pressure is comparable to the plasma pressure, strong density profile modification occurs. The profile falls steeply through the critical density n_c, to a flat plateau at about $n_c/2$. Resonance absorption occurs in p polarization, maximizing at angles of incidence $\Theta \cong 20°$. For s polarization, absorption is due to ion density fluctuations at n_c driven by the laser, and remains constant with Θ as long as the light's turning point stays on the density plateau ($\Theta \leq 45°$). The critical surface seems to be rippled due to either laser hot spots or critical surface instabilities, which we discuss below. We model this rippling by assuming the surface to be tilted randomly in all planes, with an rms angle of $\sim 8°$. The theoretically predicted absorptions are shown as the solid line in Fig. 1.

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The shapes of the theoretical and experimental curves agree well. Other absorption mechanisms give a 10% additional angle and polarization independent absorption.

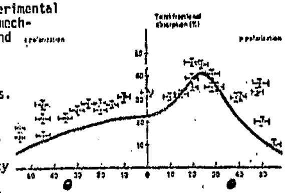

Figure 1

We have studied the formation of ripples on the critical surface using several computer simulation techniques. With ZOHAR (2 space dimensions, PIC) we found that rippling is quite sensitive to polarization. For s-polarized light of high intensity, Valeo and Estabrook[3] showed that the density depression due to the ponderomotive force is unstable to bubble formation. Closed cavities are produced which are $\sim 1\lambda_o$ in diameter and are isolated from the incident light. For circularly polarized laser light, these density structures remain open to the incident light on their low-density side. As the structures form due to the instability, dissipation by the p-polarized component increases, and overall absorption is enhanced. We inferred from our 2D studies of the different polarizations that in three spatial dimensions tubes of low density plasma are expected to form, as the surface ripples preferentially in the plane containing $\vec{k}_0$ and $\vec{B}_0$. The 3D simulations described below confirm this hypothesis.

Motivated by understanding the full polarization properties of critical surface ripples, we have begun using a 3D PIC code developed at Stanford University. The code is relativistic and electromagnetic, using a 32 x 32 x 32 mesh. The preliminary studies had triply periodic boundary conditions. To study 3D ripples caused by normally incident light, a plane wave was launched in the vacuum region onto an over dense plasma slab, with light pressure $\sim$ plasma pressure during the course of the run. Fig. 2 shows two side views of the slab late in time, when ripples have formed. The left and right views show the planes containing $\vec{B}_0$ and $\vec{E}_0$ respectively. These first 3D results show that ripples are strongest in the plane of $\vec{B}_0$, consistent with our 2D ZOHAR simulations. However, for strong enough laser fields weaker ripples will also form in the plane of $\vec{E}_0$, as shown on the right side of Fig. 2.

Figure 2

The above results are for uniformly incident light. However, spatial irregularities in the incident laser beam can produce structure on the critical surface even in p polarization, and hence enhance the absorption. A typical simulation (p polarization) of a "hot spot" 2 1/2 λ_0 in diameter shows as high as 46% absorption, compared to only 13% absorption if the same beam were uniform. Therefore, both the structure of the beam and the inherent critical surface rippling instability can enhance the efficiency of resonance absorption.

We are also studying absorption on larger spatial scales, so as to include realistic geometry and finite focal spot size. The laser light pressure makes the n_c surface convex, since steepening occurs preferentially near the intense center of the beam. As a result, absorption may be increased by 10-20%.

Steepened profiles like those predicted in Ref. 2 have recently been measured experimentally.[4] The measured profile was monotonic in density. Theory indicates that monotonic profiles will only exist when the plasma outflow velocity relative to the critical surface is subsonic.[5] If the outflow is supersonic entering the critical region, a shock forms at a density $n > n_c$, as shown in Fig. 3. *Such shocks have been seen in numerical* hydrodynamic calculations which include the laser light pressure.[6] For low-Z plasmas the shock will be collisionless; associated microinstabilities and reflected ions may play a role in energy transport.

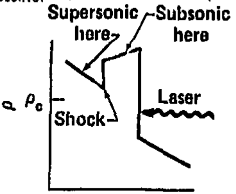

Figure 3

We have also examined[7] the heated electron spectra due to resonance absorption.[8] In 2D simulations[2] with $I_L = 3 \times 10^{14} - 10^{17}$ W/cm^2 and background temperatures $T_e = 1 - 32$ keV, the heated electrons form a Maxwellian whose (2D) temperature T_{hot} scales as $T_{hot} \approx T_e + 1.9 \times 10^{-5}\, T_e^{.11} [I_L(\lambda_o/1.06\,\mu m)^2]^{.39}$. The initial condition for this data was a density ramp of gradient scale length 1.76 λ_o. A step initial condition was also used between intensities 10^{16} and 10^{17} W/cm^2, with high enough maximum density for pressure equilibrium. The equilibrium was tested by starting with the maximum density too high and letting it fall, and conversely by starting too low and letting the maximum density increase. Similar T_{hot}'s resulted. The temperatures with the initial step profile were initially cooler, but they gradually increased to approximately (but still lower than) the values obtained with the ramp profile as the lower density plateau established itself. Absorption was (47 ± 10)% for these runs, which are all at $\theta = 24°$. The critical density scale length L obeys the scaling $L/\lambda_D \cdot (I_L \times 4.7 \times 10^{-19})^{-.48}$. A simple model for resonance absorption heating is described in Refs. 2 and 7. These results compare favorably with experiments using both lasers and microwaves.[9]

II. STIMULATED SCATTERING

Future lasers will use longer pulse lengths and produce longer density gradients. Under these circumstances stimulated Brillouin scattering (SBS) may become important. In SBS the incident light is scattered into an ion wave and a back- or side-scattered light wave. Ion heating due to the instability limits the scattering in this regime, since ion acoustic waves become strongly damped when $T_i \to T_e$. A simple model has been used to estimate the stimulated reflectivity taking into account the self-consistent ion heating. Typically, the calculated reflectivities are ~ 10% when L = 10 λ_o and ~ 50% when L = 50 λ_o, where L is the scale length of the underdense plasma. Reflectivities similar to those calculated have been recently observed in long pulse experiments on the Argus Laser[10].

A second environment where stimulated scattering may occur is in the background gas of a laser fusion target chamber, where there is a long path for stimulated Raman scattering (SRS) to decollimate the beam and cause laser energy to miss the target. For a gas density $n \sim 10^{16}$ cm^{-3}, both forward and backward SRS are strongly driven. Plasma wave trapping of electrons limits the instability growth. Forward SRS is more efficient at scattering than backward SRS, due to its higher saturation level. For 1 μm light with $I_L = 10^{15}$ W/cm^2 on target, target diameter 500 μm, and an f/3 lens, a conservative (i.e. high) estimate of the scattered light fraction is ~ 10%. This fraction is $\propto \lambda_0$, so CO_2 lasers are more likely to be decollimated. Since the SRS growth rate is very low, a small fractional amount of laser bandwidth (e.g. 10^{-3} for 1 nsec) can quench the instability.

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