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LIMITATION OF BRILLOUIN SCATTER IN PLASMAS

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Limitation of Brillouin Scatter in Plasmas*

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ABSTRACT

A simple model is proposed for the limitation of Brillouin backscatter often observed experimentally. This limitation is a natural consequence of the limited mass and heat capacity of the underdense plasma. In this model a reflection front moves through the underdense plasma supersonically. For plasmas prepared by a prepulse, the reflectivity could then be time-dependent in agreement with some recent experimental measurements.

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The efficiency with which intense laser light is absorbed is one of the most important questions for laser fusion applications. Of particular concern is the possibility that intense light may be reflected in the underdense plasma by the Brillouin and Raman instabilities. Linear theory[1] indicates that the thresholds for these instabilities are readily exceeded, and computer simulations[2-4] have shown that a large reflection can then occur in the nonlinear state. Reflection via the Brillouin instability is especially dangerous, since the principal energy transfer is from the incident light wave to the scattered one. However, there is at present very little correlation between experiment and theory. For example, experiments[5-9] have typically shown a net back reflection of order 20% for incident light intensities of $\gtrsim 10^{16}$ W/cm^2 (for 1.06 μ light). Indeed this back reflection is sometimes observed to decrease with increasing intensity.

We present theoretical estimates and computer simulations which show that a large induced reflection of intense light can occur, but that this reflection is time-dependent. In effect, a reflection front can propagate supersonically through the underdense plasma, and so the reflection persists for a limited time which depends both on the intensity and the amount of plasma present in the underdense region. We compare our results with some recent experimental results obtained at the University of Rochester in which a plasma is preformed by a prepulse and in which a large and time-dependent reflection is indeed observed.

Let us begin with some theoretical estimates to demonstrate the basic physical processes. The central feature which limits the reflection is the limited mass and heat capacity of the region of underdense plasma. Consider a preformed plasma with a density gradient length L. The number of ions per unit area available to reflect incident laser light is $\sim \frac{n_{cr}L}{2}$, where n_{cr} is the critical density and for simplicity a linear profile has been assumed. As the intense light is back-reflected, twice its momentum must be taken up by the ions, which leads to their expulsion from the region in which the reflection is occurring. The momentum transfer is described by an equation for the ion displacement ξ of the form

$$\frac{n_{cr}L}{2} M \ddot{\xi} = 2\frac{E_L^2}{8\pi} , \qquad (1)$$

where M is the ion mass and $E_L^2/8\pi$ is the light pressure. An approximate criterion for determining how much momentum the ions can take up before they are pushed out of the region is $\xi \sim L/2$. The time required for expulsion is then

$$t_r \simeq \frac{L}{\left(\frac{2m}{M}\right)^{1/2} v_{os}} , \qquad (2)$$

where m/M is the electron ion mass ratio and v_{os} is the electron oscillatory velocity in the laser light field. Hence (2) gives an estimate for how long a large reflection can persist.

Of course, the incoming flux of cold plasma from higher density competes with the above effect. Plasma simulations[10-11] of laser light absorption indicate that near n_{cr} the plasma electrons consist of a relatively cold main body with a temperature of ~1kev due to inverse bremsstrahlung plus a lower density, very hot tail due to various collective heating mechanisms. Since this low density, very hot tail is rather ineffective in reflecting the light, let's concentrate on the rate of resupply of the cold plasma. This density flux is $\sim n_{cr} \sqrt{\frac{m}{M}}\, v_{te}$, where v_{te} is the electron thermal velocity. Thus, when $v_{os} > v_{te}$, the resupply does not substantially change our model. For a main body temperature of ~1kev, the above condition is satisfied when $I \gtrsim 2 \times 10^{15}$ W/cm² for 1.06μ light.

To illustrate the microscopic behavior in more detail, we will here consider the back-scatter of light in a slab of underdense plasma with an initially uniform density. This simplification of initially uniform density does not alter the basic results, since the threshold intensities set by gradients can be far exceeded and since our momentum balance estimates depend essentially on the net amount of plasma in the underdense region. Theory for a slab of uniform density shows that light is reflected by the Brillouin instability in a distance ℓ, which has been analytically calculated in two distinct limits. When the ion waves are very weakly damped[12] ($\frac{\gamma_i}{\omega_i} \ll 1$, where γ_i is the ion wave damping rate and ω_i the ion wave frequency),

$$k_0 \ell \simeq \sqrt{2}\ \frac{\omega_0}{\omega_{pe}} \left(\frac{v_{te}}{v_{os}} \right) \qquad (3)$$

Here ω_0 (k_0) is the frequency (free space wave number) of the light wave, and ω_{pe} is the electron plasma frequency. On the other hand, if the ion waves are heavily damped,[13] then

$$k_0 \ell \sim 10 \left(\frac{\omega_0}{\omega_{pe}}\right)^2 \left(\frac{v_{te}}{v_{os}}\right)^2 \frac{\nu_i}{\omega_i} \quad . \qquad (4)$$

Computer simulations have shown that, even if the ion temperature is much less than the electron temperature initially, ions are readily accelerated to velocities $\gtrsim v_{te} \sqrt{\frac{m}{M}}$ by ion trapping in the Brillouin-generated sound waves. The ion waves then become heavily damped, and so one transfers from the weak damping to the strong damping regime. The distance over which the reflection occurs is increased, but at high intensities the reflection length even in the large damping regime is quite short.

Of course, when $\frac{v_{os}}{v_{te}} \sim O(1)$ one should extend the above solutions to allow for the influence of the light pressure on the acoustic wave. However, our principal point is that these solutions neglect the effect of the momentum transfer to the plasma which occurs when the ion waves damp. As shown by our estimates in equations (1) and (2), this secular momentum transfer introduces a new time scale. At high intensities the reflection front is <u>not</u> stationary relative to the higher density regions, but propagates through the plasma in a time $\sim L/\sqrt{\frac{m}{M}}\, v_{os}$. (In contrast, the time for instability growth and saturation is $\sim \lambda_0/\sqrt{\frac{m}{M}}\, v_{os}$, where λ_0 is the free space wavelength.)

Our estimates have been confirmed by computer simulations of Brillouin backscatter. In these simulations we propagate intense laser light from a vacuum into a plasma slab of uniform density. In order to more clearly isolate the physics, we choose the initial plasma density to be $> .25\ n_{cr}$ to exclude the Raman instability, which gives rise to less efficient reflection and can be saturated by a hot electron tail. The simulations were carried out using two different codes - a $1\frac{1}{2}$D code with particle electrons and ions and a 1-D code with fluid electrons and particle ions.[14]

This latter code allows us to more economically study long-time behavior, and comparisons show that the results from this code are in reasonable agreement with those from the more complete code. In the simulations the particles are reflected from the left side of the plasma but are re-emitted with constant flux from the right side in order to model a resupply of the simulated plasma by a reservoir of plasma at the initial temperature. This allows us to model the transmission properties of a slab of such plasma without simultaneously modeling the complicated absorption processes occurring near the critical density. Light waves exiting the plasma slab are allowed to freely propagate away.

Here we will briefly discuss a simple example motivated by experiments performed at the University of Rochester. Light of wavelength 1.06μ and intensity 5×10^{15} W/cm^2 is propagated through a 30 μ plasma slab with an initial density of $1/3n_{cr}$ and an electron temperature of 1kev. The electron-ion mass ratio is .01 and the initial temperature ratio is 5. The light reflection rapidly onsets and rises to an average value of 2/3. This reflection principally occurs in about 5 wavelengths, which is several growth lengths as estimated from Eq. 4.

However, this is not a stationary state as is clear from our momentum balance argument. A large fraction of the plasma is pushed to the right as the momentum deposition from the damped ion waves secularly accumulates. This is shown in Fig. 1, where we plot the plasma density profile (averaged over the $2k_0$ density fluctuations) from several different times in the simulation. The front of strong reflection is proceeding at a velocity of $\sim .01c$. This is approximately the rate expected from our foregoing estimates; i.e. $v_f \sim \sqrt{\frac{m}{M}}\, v_{os}$, where $\frac{m}{M} = .01$. We have also carried out several examples with more intense light, and find that the speed of the front increases approximately as the square root of the intensity as expected. The recoil of the plasma is shown even more graphically in Figures 2a and b, where we plot an ion phase space and a mean velocity profile from the simulation.

As the reflection front moves through the plasma slab, the reflection gradually decreases. This is shown by the plot of transmission versus time in Fig. 3. We have averaged this transmission over some short-time relaxation oscillations which occur at roughly the frequency of the ion waves, and which were previously pointed out in Ref. 3. Note that the reflection gradually decreases from $\sim 65\%$ to 10 in a time of $t = 1.5 \times 10^{-}$. In agreement with our estimates, this time is $L/\sqrt{\frac{m}{M}}\, v_{os}$; that is, the time for the reflection front to traverse the system. If we scale to a mass ratio appropriate for deuterium, the reflection persists for a time of $\sim$ 50 ps.

Finally we compare our results with some recent experimental results obtained at the University of Rochester. In these experiments a plasma was first formed by a prepulse of $\sim$ 1 joule of 1.06μ light on a 400μ diameter cylinder of D_2. About 1 ns later this pulse was followed by a 500 ps main pulse, and the time-dependent back-reflection was measured. Fig. 3 shows the time dependence of the reflectivity observed in an experiment in which the incident energy was $\sim$ 100J and the focal spot diameter was 70μ. A large reflected intensity - as high as 80% of the incident intensity - rapidly onsets and slowly decreases over a time of $\sim$ 50 ps. After this time the reflection drops to a much smaller value ($\lesssim 10\%$). This behavior compares favorably with [illegible] calculated in our simulation. (For this experiment we have estimated a preformed plasma with a density gradient of $\sim 30\ \lambda_0$.

This corresponds to the same amount of plasma present in a 30 λ plasma slab with an initially uniform density of $\sim 1/3\, n_{cr}$.)

Several other features observed in experiments are also consistent with this picture of the reflectivity. First as the intensity is increased, the large reflectivity persists for a shorter time. This gives rise to a <u>decrease</u> in the net reflectivity of the 500 ps pulse with intensity as observed in the experiments at the University of Rochester. Furthermore, this decrease in the reflectivity onsets for an $1 - 2 \times 10^{14}\ \mathrm{W/cm^2}$, also as expected, since this is roughly the intensity for which $v_{os} \approx v_{te}$ for the cold main body. On the other hand, in experiments in which there is no prepulse, we estimate little reflectivity of very intense light since a sufficiently extended region of underdense plasma is not formed, (i.e. there is no sizeable preformed plasma which must be first displaced). This may account for the low reflectivity observed in many short pulse experiments with high intensity light. Likewise, if there is a prepulse which precedes the main pulse by too long ($\gtrsim$ 10 ns), not much preformed plasma survives for the main pulse. In this regard, it should be noted that there are also critical surface phenomena which aid in reducing the flow of cold plasma out from the critical surface and thus maintaining a large density gradient.

Lastly, note that the frequency shift calculated in our model is larger than that predicted by linear theory because during the period of large reflectivity the plasma is accelerated inward relative to the higher density plasma. Of course, the net frequency shift observed in the laboratory is a combination of this red shift plus a blue shift due to the overall expansion of the upstream plasma. The increased red shift may be sufficient to yield a net red shift in the frequency of the reflected light.

In summary, we have proposed a model for the limitation of the Brillouin back-scatter often observed experimentally. This limitation is a natural consequence of the limited mass and heat capacity of the underdense plasma. For a preformed plasma, a large reflection can persist for a time of $\sim L/\sqrt{\frac{m}{M}}\, v_{os}$, as the reflection front moves through the plasma. Our results are consistent with some recent experimental results showing a large but time-dependent reflectivity in a plasma formed with a prepulse. For simplicity we have discussed back-scatter, but similar results should also obtain for side-scatter (the momentum transfer is less by a factor of $\sqrt{2}$). It should be noted that 2-D effects could further reduce the time over which a large reflectivity can occur. For example, the incident light may form narrow filaments, expelling the plasma laterally.[15]

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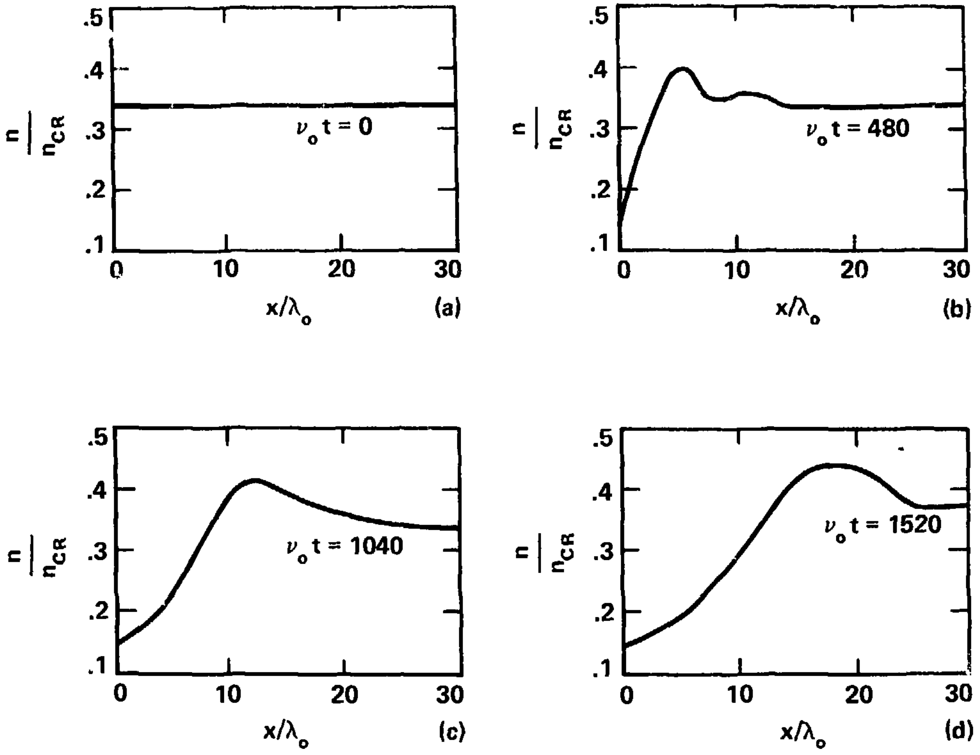
FIGURE CAPTIONS

Fig. 1: The ion density profile at four different times in the simulation.

Fig. 2: a) The ion phase space plot (p_x vs x) and
b) The mean velocity profile from the simulation.

Fig. 3: The evolution of the light transmission through a 30 plasma slab. The transmission has been averaged over relaxations oscillations which have a period of t 300.

Fig. 4: Time dependent reflectivity measurements (from Ref. 5) The incident pulse is displayed above the reflected one (not the same scale) for reference.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.4
.3
.2
.1
n/n_{CR}
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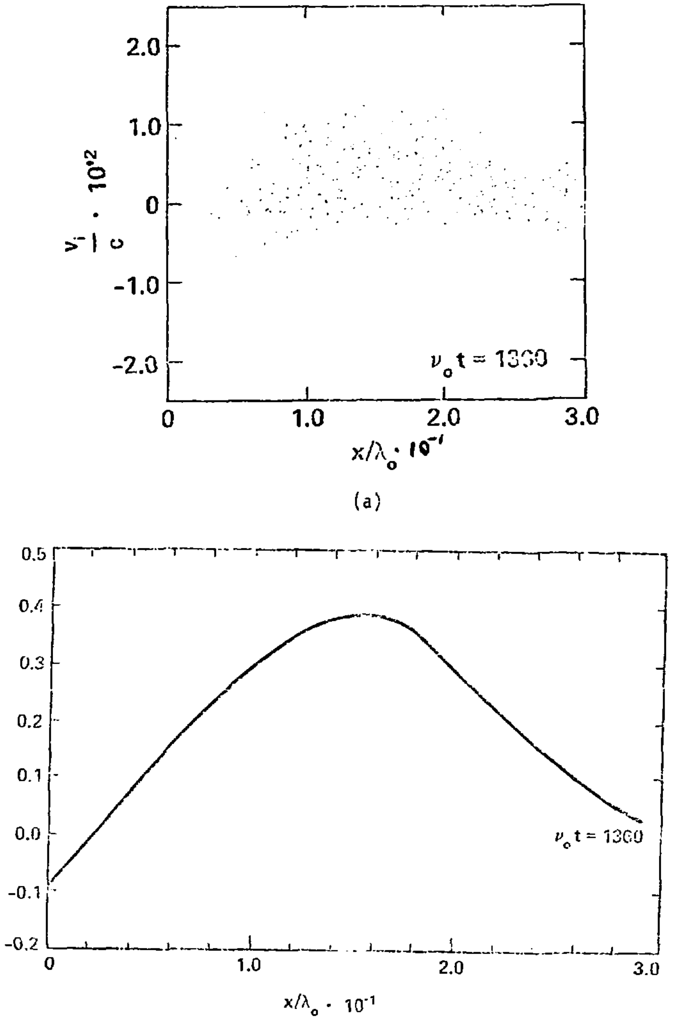
0
10
20
30
x/λ_o
(a)
$\nu_o t = 480$
(b)
$\nu_o t = 1040$
(c)
$\nu_o t = 1520$
(d)

FIGURE 1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0
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-2.0
$\frac{v_i}{c} \cdot 10^2$
$\nu_o t = 1300$
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1.0
2.0
3.0
$x/\lambda_o \cdot 10^{-1}$
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
$\frac{v_i}{c} \cdot 10^2$
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3.0
$x/\lambda_o \cdot 10^{-1}$

(a)

(b)

FIGURE 2

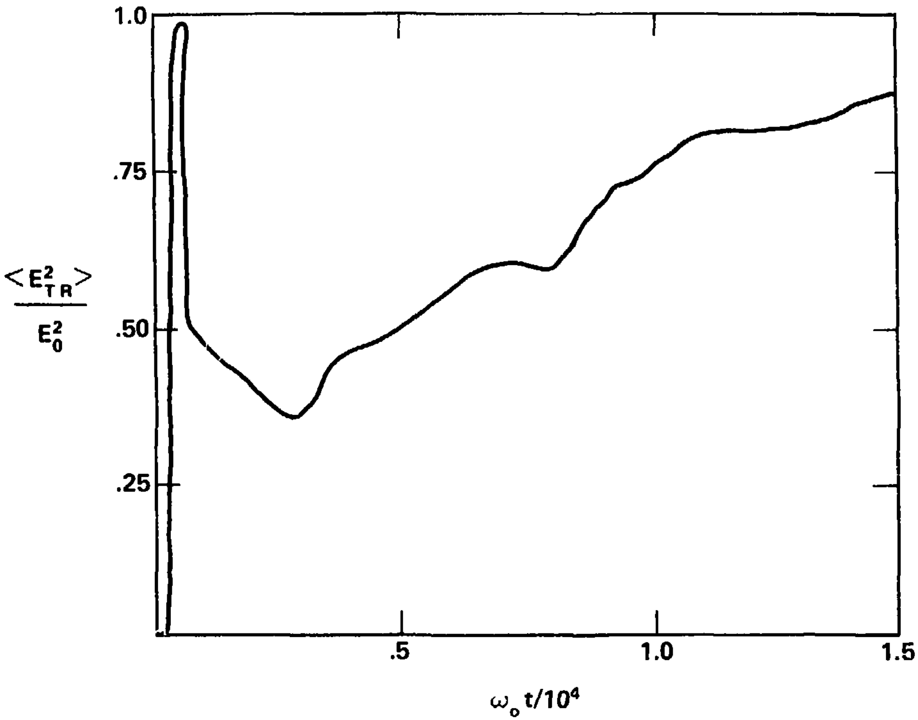

FIGURE 3

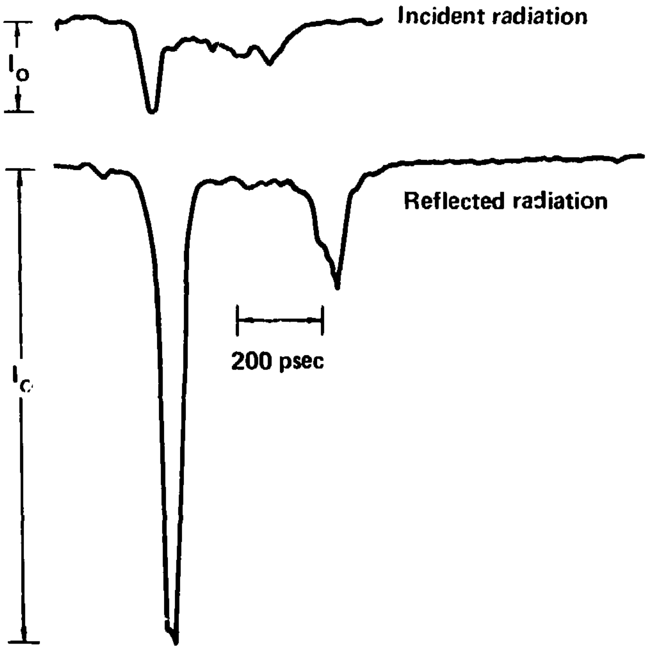

FIGURE 4