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Limitation of Brillouin Scattering in Plasmas*

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It is shown that Brillouin scattering of intense laser light in plasmas can be limited by momentum and energy deposition as a result of reflection of the light. The calculations compare favorably with some recent experimental results.

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[2-5] 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[6-10] have typically shown a net back reflection of order 20% for incident light intensities of $\gtrsim 10^{16}$ W/cm^2 (for 1.06-μm 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 inherently limited by momentum and energy deposition as a result of reflection of the light in the underdense plasma. This momentum deposition drives a reflection front supersonically through the underdense plasma. Consequently, the induced reflection persists for a limited time which depends on both the intensity and the amount of plasma present in the underdense region. We compare our results with some recent experimental results[6] obtained at the University of Rochester in which a large and time-dependent reflection has been observed.

The basic physical processes can be simply illustrated by appealing to an idealized model. Assume that the reflection length l is much less than the density scale length L of the underdense plasma. Analytic calculations of this reflection length in both the weakly[11] and the strongly[12] damped acoustic-wave limits show that this condition is easily obtained. Further assume that the ion-wave-damping decrement satisfies the inequality $\nu_i > c_s/l$, where c_s is the sound speed. Then the ion waves deposit their momentum and energy in the interaction region. Computer simulations[2,3] have shown that, even if the ion waves are initially weakly damped, they become heavily damped in the nonlinear state because of ion trapping.

Finally, assume that the energy density of the electromagnetic wave exceeds the kinetic-energy density of the plasma. This assumption is motivated by simulation studies[13] of laser-light absorption. These studies indicate that near the critical density (n_{cr}) the plasma electron energy distribution consists of a relatively cold main body with a temperature of ~ 1 keV due to inverse bremsstrahlung, plus a lower-density very hot tail due to various collective heating mechanisms. Since this lower-density hot tail is rather ineffective in reflecting the light, we neglect it here. For a main body temperature of 1 keV, our last assumption is satisfied when the intensity $I > 2 \times 10^{15}$ W/cm^2 for 1.06-μm light.

With these assumptions, consider the macroscopic behavior in the frame moving with the reflection front. As illustrated in Fig. 1, take total light and plasma reflection from opposite sides of the front, and designate the incoming (reflected) plasma density and velocity by n^+ (n^-) and v^+

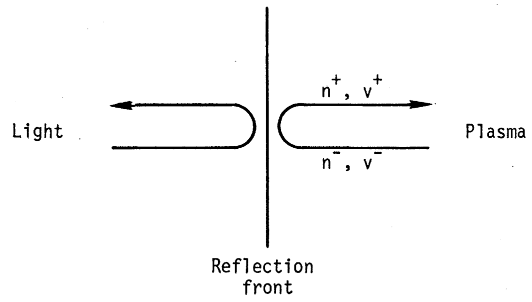

FIG. 1. A sketch of a very simple model of the light-plasma interaction in a frame moving with the reflection front.

(v^-), respectively. Number and momentum conservation then give

$$n^-v^- = n^+v^+, \quad (1)$$

and

$$M(nv^2 + n^+v^{+2}) = 2E_L{}^2/8\pi, \quad (2)$$

where M is the ion mass and $E_L{}^2/8\pi$ is the light pressure. Of course, the momentum fluxes of the particles can be described more accurately as second moments of a distribution function, but Eq. (2) will suffice for these estimates. If we crudely estimate $v^- \sim v^+$, then the velocity of the front relative to the incoming (upstream) plasma is

$$v^+ \sim \mu(n_{cr}/n)^{1/2} v_{os}, \quad (3)$$

where μ^2 is the electron-ion mass ratio, and v_{os} is the oscillatory velocity of an electron in the laser-light field. The time required for this reflection front to propagate through the underdense plasma is then

$$t_r \simeq L/(\mu v_{os}), \quad (4)$$

where we have assumed a linear profile with scale length L. Hence t_r gives an estimate for how long a large reflection can persist.

Our principal point is that the secular momentum and energy transfer due to the damping ion waves introduces a new time scale. For high-intensity light the reflection front is not stationary relative to the higher-density regions but propagates through the underdense plasma in a time $\sim L/\mu v_{os}$. In contrast, the time for instability growth and saturation is $\sim \lambda_0/\mu v_{os}$, 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 an initially uniform slab of underdense plasma. 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 and energy-balance arguments depend essentially on the net amount of plasma in the underdense region. In order to isolate the physics more clearly, we choose the initial plasma density to be $> 0.25 n_{cr}$ 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 $1\frac{1}{2}$-dimensional (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 study long-time behavior more economically, 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 occuring near the critical density. Light waves exiting from the plasma slab are allowed to propagate freely away.

Here we will briefly discuss a simple example motivated by experiments performed at the University of Rochester. Light of wavelength 1.06 μm and intensity 5×10^{15} W/cm^2 is propagated through a $30\lambda_0$ plasma slab with an initial density of $\frac{1}{3} n_{cr}$ and an electron temperature of 1 keV. The electron-ion mass ratio is 0.01 and the initial temperature ratio is 5. The light reflection rapidly begins and rises to an average value of $\sim\frac{3}{4}$. This reflection principally occurs in about 5 wavelengths, which is several growth lengths as computed theoretically.

However, this is not a stationary state as is clear from our simple model. A large fraction of the plasma is pushed to the right as the momentum and energy deposition from the damped ion waves secularly accumulates. This is shown in Fig. 2, 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 $\sim 0.01c$. This is approximately the rate expected from our foregoing estimates, i.e., $v_f \sim \mu v_{os}$, where $\mu^2 = 0.01$. We have also carried

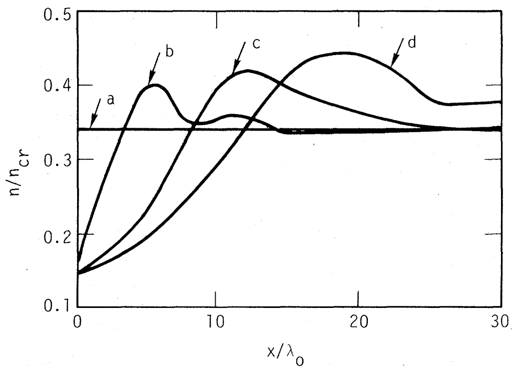

FIG. 2. The computed ion-density profile, a at $\nu_0 t = 0$; b, $\nu_0 t = 480$; c, $\nu_0 t = 1040$, and d, $\nu_0 t = 1520$ ($\nu_0 = \omega_0/2\pi$). These results are from a particle simulation: $T_e = 1$ keV and $T_e/T_i = 5$ initially.

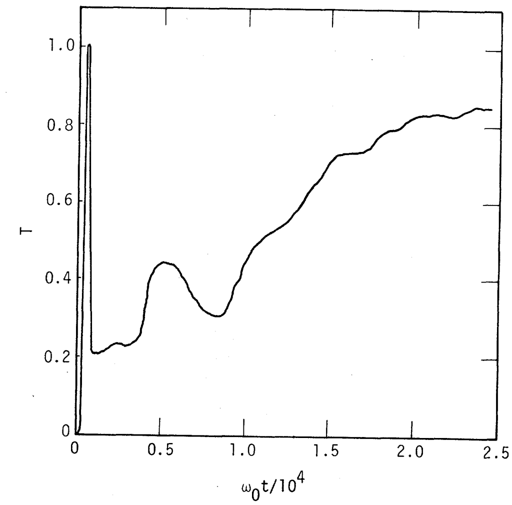

FIG. 3. The evolution of the light transmission through a $30\lambda_0$ plasma slab. The transmission has been averaged over relaxation oscillations which have a period of $\omega_0 t \sim 300$. These results are from the hybrid simulation: $T_e = 1$ keV and $T_e/T_i = 5$ initially.

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.

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 ~ 80% to ~ 15% in a time of $\omega_0 t = 2 \times 10^4$. In agreement with our estimates, this time is $\sim L/(\mu v_{os})$; 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 ~ 50 psec.

Finally, we compare our results with some recent experimental results obtained at the University of Rochester.[6] In these experiments a 500-psec pulse of 1.06-μm light (preceded by a prepulse) was focused on a 400-μm-diam cylinder of D_2, and the time-dependent back reflection was measured. In experiments in which the incident energy was ~ 100 J and the focal-spot diameter was ~ 60 μm, a large reflected intensity—as high as 80% of the incident intensity—rapidly began and slowly decreased over a time of ~ 60 psec. After this time the back reflection dropped to a much smaller value ($\lesssim$ 10%). This behavior compares favorably with that 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 $30\lambda_0$ plasma slab with an initially uniform density of $\sim \frac{1}{3} n_{cr}$.)

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 *decrease* in the net reflectivity of the 500-psec pulse as the intensity is increased. This decrease has been observed in the University of Rochester experiments. Furthermore, this decrease in the reflectivity is observed to begin for $I \sim 2 \times 10^{15}$ W/cm^2, also as expected, since this is roughly the intensity for which $v_{os} \gtrsim v_{te}$ for the cold main body. On the other hand, in experiments in which there is a short, rapidly rising, laser pulse, we estimate little reflectivity of very intense light since there is no sizable performed plasma which must be displaced when the light reaches high intensity. This may account for the low reflectivity observed in many short-pulse experiments with high-intensity light. In this regard, it should be noted that there are also critical-surface phenomena[13] which reduce the flow of cold plasma out from the critical surface and thus help to maintain a large density gradient.

Lastly, note that the frequency shift calculated by such a 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.

For simplicity we have discussed backscatter, but similar results should also obtain for sidescatter (the momentum transfer is less by a factor of $\sqrt{2}$). It should be noted that 2D 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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Ion-Induced Pinch and the Enhancement of Ion Current by Pinched Electron Flow in Relativistic Diodes*

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A new model for time-dependent and steady-state ion and electron flow in large-aspect-ratio diodes is constructed. The electron trajectories are computed with use of the self-consistent fields calculated during the initial ion motion. The dynamic formation of a tightly pinched electron flow is qualitatively explained. Very large ion currents, nearly equal to the electron current, are predicted for flat solid cathodes, when steady-state flow is achieved.

Dynamic formation of pinched electron flow has been observed in large-aspect-ratio diodes with hollow[1] and solid cathodes.[2-4] In the hollow-cathode geometry a ring of electrons hitting the anode plane is observed to collapse radially, with typical velocities of ~0.3 cm/nsec, forming a pinch of 1–3 mm diameter. Very similar phenomena are also observed when solid cathodes are used.[3] In early time, before the anode plasma has been formed, only electron flow will exist and its