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THEORETICAL INTERPRETATIONS OF ENHANCED LASER LIGHT ABSORPTION

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THEORETICAL INTERPRETATIONS OF ENHANCED LASER LIGHT ABSORPTION*

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Intense laser light is not efficiently absorbed classically but can be absorbed by its conversion to electron plasma waves near the critical density. The physical mechanisms for this conversion are discussed, and some simple estimates for heating by plasma waves are applied to some recent experiments. Several effects which strongly influence the absorption of high intensity light are emphasized, including a nonlinear steepening of the plasma density profile which is demonstrated in computer simulations. Finally the possibility of an induced reflection of laser light due to instabilities in the underdense plasma before the critical density is also discussed. Such stimulated reflection can be particularly important in plasmas with very long density gradients.

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I. Introduction

The absorption of intense laser light is obviously one of the very important questions for laser fusion applications. In experiments this absorption has been observed to be substantially more efficient than expected on the basis of classical inverse bremsstrahlung. An absorption efficiency of $\sim 70\%$ has been typically observed in experiments with slab targets¹⁻⁴ — even using laser light intensities exceeding 10^{16} W/cm² (Nd). It should be noted that a number of experiments with curved targets such as spheres or cylinders have shown a somewhat lower absorption efficiency of $\sim 30\%$, with about half the energy lost to refraction around the target. But even in these experiments the absorption is usually found to be greater than expected classically at high intensities.

We can theoretically understand this enhanced absorption on the basis of collective processes in the plasma; i.e., the conversion of laser light into plasma waves. An overview of our present understanding of laser light absorption will be presented. The aim is to convey the physical ideas using very simple estimates rather than elaborate on the latest technical detail. We will first discuss classical inverse bremsstrahlung, showing why it becomes inefficient even at moderate intensities ($10^{13} - 10^{14}$ W/cm², Nd), and then show

how a plasma can be heated collectively. The discussion is made more concrete by applying our estimates to some recent laser plasma experiments. We conclude with a brief discussion of light absorption at high intensity ($I \approx 10^{15}$ W/cm², Nd), emphasizing the importance of density profile modifications and the possibility of stimulated scattering of light from the plasma.

II. Classical Inverse Bremsstrahlung

First let's look at some simple estimates in order to see what to expect from classical inverse bremsstrahlung. In more physical terms, this is simply Joule heating of the plasma by the high frequency laser light. The rise in the kinetic energy of the plasma is

$$\frac{dKE}{dt} = \nu_{ei} \frac{E_L^2}{8\pi},$$

where ν_{ei} is the electron-ion collision frequency and E_L is the electric field of the laser light. As is well known, $\nu_{ei} \propto 1/\theta_e^{3/2}$, where θ_e is the electron temperature. The decrease with temperature follows from general properties of the Coulomb force law. And so the problem becomes obvious. A hot plasma becomes collisionless, meaning that Joule heating becomes ineffective.

We can illustrate the numbers involved by a very simple "back-of-the-envelope" calculation. Consider the propagation of light into an inhomogeneous plasma slab, assuming for simplicity a linear rise in density from zero to the critical density in a distance L . Then a simple integration shows how the light is classically attenuated as it traverses the plasma (in and out).

$$I_{\text{ABS}} = I_0 [1 - \exp(-\frac{32}{15} k_0 L \frac{v_{\text{CR}}}{\omega_0})], \quad (1)$$

where I_{ABS} is the absorbed intensity, I_0 the incident intensity and v_{CR} the collision frequency evaluated at the critical density. The collision frequency depends on temperature. For our purposes we will crudely estimate a temperature by using the flux limit, which essentially determines the minimum temperature the plasma must reach in order to carry off the absorbed energy. So, if anything, we are giving an over-estimate of classical absorption. With a little algebra, we then obtain

$$\frac{I_{\text{ABS}}}{I_0} \ln \left[1 - \left(\frac{I_{\text{ABS}}}{I_0} \right) \right]^{-1} = 10^{11} k_0 L. \quad (2)$$

This estimate of the fractional absorption versus incident intensity is plotted in Figure 1. A scale length of $100 \lambda_0$ (free space wavelengths) has been assumed, a value estimated for some experiments to be discussed shortly. The absorption efficiency is quite good for intensities up to $\sim 10^{13} \text{ W/cm}^2$ but then falls

off abruptly. This decrease reflects the "bleaching out" of the plasma-the fact that as it becomes hot, it becomes relatively collisionless. Even sacrificing efficiency, one can only classically absorb intensities of $\sim 10^{14}$ W/cm², which corresponds to heating the plasma to temperatures of $\sim .5 - 1$ keV. Now obviously one can change these numbers somewhat by using high Z targets or different scale lengths, and one can do much more sophisticated calculations, but this calculation is indicative of what to expect from classical heating.

III. Plasma Heating by Collective Processes

However, there is a way to efficiently heat even a collisionless plasma. The laser light can convert its energy into electron plasma waves. These electron plasma waves, which are simply high frequency oscillations of charge density, in turn accelerate and heat the electrons. The generation of electron plasma waves is most efficient near the critical density surface, where the laser light frequency equals the local electron plasma frequency. Here virtually any spatial variation in ion density will couple laser light into electron plasma waves.⁷ Physically this is very simple to understand. As illustrated in Figure 2, the electric field of the laser light rapidly oscillates electrons from regions of higher density to regions of lower density, and vice versa, at a frequency near that at which the plasma naturally responds.

The spatial variations in ion density are produced in many different ways.

1. They can be spontaneously generated from the noise by parametric instabilities.⁸ In the simplest case, such instabilities can be thought of as the resonant decay of a light wave into an electron plasma wave and an ion wave.
2. The gradient in ion density can result from the plasma expansion into the vacuum, provided the light is obliquely incident. This is the well-known phenomenon of resonant absorption, discussed in standard textbooks.^{9, 10}
3. Particularly at high intensities ($\sim 10^{16}$ W/cm²), the variations in ion density can be generated by many additional processes, such as laser light filamentation and streaming instabilities due to heat transport.¹¹ Such processes are especially important since large density fluctuations efficiently couple laser light into electron plasma waves even when the coupling is quite off-resonant.¹² Roughly the frequency mismatch normalized to the laser light frequency can be as large as the relative magnitude of the density fluctuation, i.e., $\frac{\Delta\omega}{\omega_0} \sim \frac{\delta n}{n_0}$. Hence the absorption is not so finely tuned to the critical density surface and

not so sensitive to density profile changes which can be quite substantial at high intensities.

So there are many different ways to couple the light into electron plasma waves. It's worthwhile to quickly review how the plasma waves in turn heat the particles. The charge density fluctuations have an associated high frequency electric field which can be described in terms of waves of the form $E_k \sin(kx - \omega t)$. Here E_k is the Fourier amplitude, k the wave number and ω the frequency ($\omega \sim \omega_{pe}$). Very slow electrons see only a rapidly oscillating field and are not heated. On the other hand, those electrons with velocity $\sim \omega/k$ experience an essentially constant field and are efficiently accelerated. The details of the energy transfer depend on the velocity distribution of the particles. But the important point is that both instabilities and resonant absorption tend to produce high phase velocity electron plasma waves, ($\omega/k \gtrsim 3 v_{te}$ where v_{te} is the electron thermal velocity), and so a quite energetic heated electron spectrum results. In contrast, processes such as electron-ion streaming instabilities due to heat transport generate short wavelength ion fluctuations which then (off-resonantly) couple laser light into much slower electron plasma waves. A less energetic spectrum of heated electrons then results, as confirmed in computer simulations.

IV. An Estimate of Instability Heating

Let us again consider a very simple example in order to more quantitatively illustrate heating via collective processes. In particular,

consider rather moderate laser light intensities near those at which the classical heating strongly diminishes. We will see that the description becomes more complex for higher laser light intensities like $10^{15} - 10^{16}$ W/cm², since a larger number of processes can enter and profile modifications become quite large. Hence this latter regime is less amenable to "back-of-the-envelope" estimates.

With these restrictions, we again consider laser light as normally incident on a inhomogeneous plasma slab and now estimate the effect of instability heating. Of course, if light is obliquely incident with the proper polarization, it can be partially absorbed by resonant absorption. But at moderate intensities this is an additive effect; that is, we are probably underestimating the collective heating which is fine for this discussion.

Simple models of instability heating near the critical density have been investigated in some detail both analytically¹³ and in computer simulations.⁸ For our purposes, two points suffice. First, there is an efficient plasma heating which can be estimated in terms of an effective collision frequency (ν^*) which is $\nu^* \sim 2\gamma$. Here γ is the linear growth rate of the instability. Secondly, there is a production of suprathermal tails on the electron distribution function. Both these features have been observed in microwave experiments¹⁴ in which the turbulence can be directly probed.

It is straight-forward to apply these estimates to compute the energy absorption as a function of intensity for the same case in which

we have estimated the classical absorption. The result is shown in Figure 3, where the fractional absorption is plotted versus intensity. The absorption due to instabilities starts to be appreciable for an intensity of $\sim 10^{13}$ W/cm² and steadily increases with intensity as the plasma is driven more and more turbulent. Comparing with the results in Figure 1, we note that 10^{13} W/cm² is roughly the intensity at which the classical absorption begins to rapidly diminish. This complementary behavior is not accidental but reflects some very simple physics. As the plasma becomes hot and relatively collisionless, the Joule heating goes away but plasma waves are then easily excited. As already mentioned, we shouldn't extrapolate our estimate for instability heating to very large intensities because profile modifications can limit the efficiency of instability heating vis-a-vis other mechanisms.

V. A Comparison with Experiments

It is instructive to apply these estimates to some recent laser plasma experiments. These experiments² were carried out by Professor Yamanaka and colleagues in Japan. They focused a 2 ns pulse length Nd laser on a D₂ slab. In these experiments the intensity ranged from $\sim 10^{13}$ W/cm² to $\sim 3 \times 10^{14}$ W/cm². Figure 4 shows their measurements of electron temperature versus intensity as deduced from x-ray measurements. In the lower part of this figure, we have replotted our estimates of the absorption efficiency due to both inverse bremsstrahlung and instability heating.

The observed absorption remained λ 80% for all intensities. We note that this absorption is larger than estimated classically at the higher intensities but is readily accounted for by instability heating. More convincingly, above an intensity of $\sim 2 \times 10^{13}$ w/cm², they deduce two distinct electron temperatures from the x-ray measurements. This represents the onset of non-Maxwellian velocity distributions, a signature of heating via plasma waves. Indeed this onset occurs at an intensity near that for which we have estimated the onset of substantial instability heating, as shown by the lower curve. This represents reasonable evidence that a plasma can in fact be efficiently heated by the conversion of laser light into electron plasma waves.

VI. Light Absorption with Density Profile Modification

We have concentrated on presenting the basic ideas with simple estimates. Lest we oversimplify the complexity of quantifying the light plasma interaction, let us conclude with a brief discussion of several important complications which enter for high intensity light. First it becomes essential to allow for the reaction back of the strong turbulence on the plasma density profile. This is particularly true since the electron plasma wave generation most efficiently occurs at preferred values of the density; i.e., when the density is within $\sim 20\%$ of the critical density.

Strong density profile modification¹⁵ has been clearly established in recent computer simulation studies of laser light absorption near the critical density. These studies use a 2-D particle code¹⁶ which solves the complete set of Maxwell's equations and allows for fully relativistic particle dynamics. Hence the simulations self-consistently treat the laser light, the plasma turbulence both parallel and orthogonal to the direction of the density gradient, and the reaction of the turbulence back on the density profile. Their principal limitation lies in the somewhat limited region of plasma which can be simulated on the fine time and space scales characteristic of the turbulence. However, this is not too severe a restriction for a study of processes near the critical density, since the density profile becomes quite steep nonlinearly.

A typical nonlinearly steepened density profile is shown in Figure 5. This is a plot of the spatial profile of ion density from a 2-D simulation in which the laser light is obliquely incident on a plasma slab. The light intensity is 5×10^{15} W/cm², the background plasma temperature is 4 keV, and the angle of incidence is 24°. The laser light propagates into the plasma and both resonantly absorbs and instability heats near the critical density. However, the large plasma wave fields then eject plasma by their ponderomotive force and by the strong localized heating. As shown in Figure 5, there results a sharp step from sub to super-critical density. The effective gradient in density becomes quite steep, for example, a jump in density of $.6 n_{CR}$ in a distance of $1/3 \lambda_0$.

This profile steepening is easy to understand physically. Basically one has a freely expanding plasma to which a pressure is being applied at some preferred densities; i.e., near the critical density. The density locally piles up behind this region, forming a sharp step -- an effect first pointed out by Ray Kidder.¹⁷ Such a profile modification has been recently observed in microwave experiments¹⁸ and has also been inferred from laser plasma experiments.⁴

The nonlinear steepening has a number of important consequences for the light absorption. For one thing, instability heating at the critical surface is strongly reduced since there is only a small region of plasma then accessible to the instability generation. Instability heating can still take place in the lower density region before the step, but simulations indicate that this plateau is at too low a density for efficient instability generation for light intensities greater than $\sim 3 \times 10^{14}$ W/cm². (This number can be substantially increased if the electron transport is inhibited due to magnetic fields, for example.) On the other hand, the steepening favors resonant absorption since the critical density surface becomes more accessible to the obliquely incident light. The absorption in this simulation is 60%, with over 80% of this due to resonant absorption. The profile modification also strongly affects resonant absorption. For example, it much reduces the heated electron energies, since the plasma oscillations then have a shorter wavelength and thus effectively a lower phase velocity.

The intensity thresholds for these instabilities are usually determined by plasma inhomogeneity²² which limits the region over which the interaction can take place. Sidescatter of the light is often preferred, since the light wave generated in this direction experiences the least inhomogeneity. However, in many experiments the focal spot is small and has even finer scale structure (hot spots), so that sidescatter is not really preferred over backscatter. Hence let's here consider the simpler and more tractable case of backscatter.

Figure 6 shows a plot of back reflection as a function of intensity as computed in a one-dimensional particle simulation code.²¹ The points denote the simulation results, and the line shows a theoretical prediction of the reflection using a fluid model of the plasma (neglecting wave particle interactions). For these results, the plasma has a initial linear rise in density from 0 to $.6 n_{CR}$ with an effective density gradient of 16μ , and the initial plasma temperature is 1 keV. Appreciable reflection onsets for an intensity of $\sim 2 \times 10^{15} \text{ W/cm}^2$ and rapidly increases to a value of 50% for an intensity of 10^{16} W/cm^2 . It should be noted that these results are averaged over a time which is many instability growth times but which is still short on hydrodynamic time scales. For much longer density gradients the short-term reflection becomes even larger and approaches the theoretical limit of over 90%.

Experiments to date have not shown a large net stimulated scattering. The total energy reflected back into the lens is typically measured to

It should be emphasized that more complicated models are needed to quantitatively predict the light absorption at high intensity. These complications include the generation of short wavelength ion fluctuations by heat flow into the overdense plasma, the production of dc magnetic fields, a potential hydrodynamic break-up of the critical density surface,¹⁹ and the allowance for spatial variations in the intensity profile of the incident light. Furthermore, some absorption also occurs in the underdense plasma where the density is less than the critical density due to such processes as the $2\omega_{pe}$ instability, in which the light decays into two electron plasma waves.

VII. Stimulated Scattering of Laser Light

Collective processes in the underdense plasma are especially important for plasmas with long density gradients, since part of the light can be reflected before it reaches the critical density. This induced scattering^{20,21} of the light occurs due to instabilities in which the light decays into another (scattered) light wave plus either an ion or electron plasma wave. The strongest reflection occurs due to the instability which involves ion waves (the Brillouin instability). This instability occurs throughout the underdense plasma, although it becomes quite weak in the very low density regions since the ion waves are then heavily damped.

be $\sim 10 - 20\%$. However, the experiments with very intense light ($\sim 10^{-6}$ W/cm²) are generally characterized by rather short density gradients ($10 - 30 \mu$) and so are not very severe tests. This is particularly true when one takes into account that there are a number of long-term effects which can limit the time over which the strong reflection occurs.

Long-term ion heating is especially effective in limiting the reflection in plasmas with short density gradients. In the reflection process, a small fraction of the light energy is deposited in the ion waves and then damped into the ions. As shown by the Manley-Rowe relations, this fraction is $\Delta\omega/\omega_0$, where $\Delta\omega$ is the ion wave frequency. The massive ions transport energy very slowly, and so even a small deposition of energy drives them to a very large effective temperature, which can turn off the instability. Indeed, recent time-resolved measurements⁵ of back reflected light at the University of Rochester have shown a large reflection for the first 50 - 100 ps of a 500 ps pulse. A simple calculation shows that 50 ps is roughly the time needed to heat the ions in the underdense plasma to a temperature of several keV, which makes the ion waves heavily damped. Clearly more work is needed to better understand when a large reflection can occur and which long-term effects may possibly limit it, particularly in plasmas with long density gradients.

VIII Summary

In conclusion, we have given a brief overview of how intense laser light is absorbed. Intense light is not efficiently absorbed

classically but can be absorbed by its conversion to electron plasma waves near the critical density. The physical mechanisms for this conversion have been discussed, and some simple estimates of heating by collective processes have been applied to some recent experiments. Several effects which strongly influence the absorption of high intensity light have been emphasized, including a nonlinear steepening of the plasma density profile which has been demonstrated in computer simulations. Finally, the possibility of a strong induced reflection of light due to instabilities in the underdense plasma has been pointed out. Such stimulated reflection can be particularly important in plasmas with very long density gradients.

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FIG. 1

FIG. 2

FIG. 3

FIG. 4

FIG. 1

FIG. 6

FIGURE CAPTIONS

- Fig. 1: An estimate of the fractional absorption due to inverse bremsstrahlung as a function of laser light intensity.
- Fig. 2: A schematic which illustrates how laser light is converted into electron plasma waves near the critical density.
- Fig. 3: An estimate of the fractional absorption due to instabilities near the critical density as a function of laser light intensity.
- Fig. 4: Measurements of electron temperature versus laser light intensity (from Ref. 1). The lower curves are the estimates of light absorption as a function of intensity given in Figs. 1 and 3.
- Fig. 5: A plasma density profile from a two-dimensional computer simulation of laser light absorption.
- Fig. 6: The laser light reflection due to the Brillouin instability versus intensity. The computer simulation results are averaged over a time of ~ 300 light periods.

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