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TWO DIMENSIONAL SIMULATIONS OF INTENSE LASER IRRADIATION OF UNDERDENSE PLASMAS

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INTRODUCTION

The interaction between an intense laser and an underdense plasma results in many different phenomena. In particular, the interaction may result in collective processes called parametric instabilities, some of which produce plasma waves. The plasma waves can eventually produce energetic electrons as they damp away their energy. The generation of energetic electrons is detrimental for laser fusion, essential for plasma particle accelerators and essential in current drive in tokamaks, to name a few subject areas.

One process that produces plasma waves is the scattering of the incident light off a plasma wave into another light wave. This is called Stimulated Raman Scattering (SRS). SRS has been studied in detail through theory, experiments and computer simulations. The simulations studies have predominantly been carried out in one dimension (1D) over a very extensive parameter range. These simulations have provided important insight into the generation of energetic electrons and the competition between Raman backscatter (RBS) and Raman forwardsscatter (RFS). Back and forward refer to the direction of the scattered light with respect to the incoming light. In one dimension the plasma wave always propagates in the forward direction.

The previous two dimensional (2D) simulations have been done for both homogeneous and inhomogeneous plasmas with densities near quarter critical. The density where the background plasma frequency equals the light's frequency is called the critical density. The 2D simulations have indicated some of the limitations of the 1D results. For example, they reveal the importance of Raman side scatter (RSS), filamentation and two plasmon decay. Two plasmon decay is a parametric instability that also generates plasma waves and it can only occur near the quarter critical density.

In this paper we present results from two dimensional particle simulations that further isolate SRS. The 2D, relativistic, electromagnetic particle code WAVE was used. In the simulations the laser light impinges on finite homogeneous plasmas with densities significantly
FIGURE 1. Fourier spectrum of the transverse and longitudinal electric fields at $t = 200 \omega_0^{-1}$ on log scales.
(a) The transverse field showing a compact pattern which is indicative of resonant back and side scatter.
(b) The corresponding longitudinal electric field showing the high $k$ modes of resonant back and side scatter. (Note the scales are different.)
FIGURE 2. Fourier $\vec{k}$ spectrum of the longitudinal electric field on log scales. (a) The circular shape at $t = 260 \omega^{-1}$ corresponds to Raman back, side and forward scatter. (b) At $t = 360 \omega^{-1}$ a convex pattern is visible since the large $k$ modes are Landau damped. (Note the scales are different.)
the RBS-RSS modes seem to agree best with the temporal growth rate when rise-time considerations are taken into account. We previously gave an explanation as to why the absolute growth rate was not observed. We measure the growth rate by monitoring the radiation spectrum leaving the left and right hand boundaries. (The laser was launched from the left.)

Interestingly, we do not find a variation in growth rates as a function of the exit angle of the scattered light wave. This appears to contradict linear theory which says that the growth rate is proportional to $|k|$ which changes significantly with angle. Furthermore, we observe that the modes with the largest growth rates are $m = 0,1,2,4,5,$ and 7 where $k = 2\pi m/L$. At the moment we have no satisfactory explanation as to why modes 3 and 6 are less significant. The point to be made is that the modes do seem to communicate with each other.

When measuring the convective growth rate of a single pulse, by definition, it is necessary to be in the pulse's frame. On the other hand, in 1D if many pulses are being amplified simultaneously then by remaining at one point in space it is still possible to obtain the temporal growth rate. In 2D the propagation direction and shape of the pulse needs to be considered when measuring growth rates. This complication may explain the lack of an angular dependence in the measured growth rates. A similar qualitative behavior was observed for the forward scattered light. When mobile ions are used the observed growth behavior differs considerably from that in the fixed ion case. Part of the difference can be explained by the fact that although the temperature ratio, $T/e^{-1} = 1$, the Stimulated Brillouin instability can still occur because the instability is occurring in the strongly coupled regime. In this regime the pump determines the properties of the ion modes. As early times the measured growth rate seems to agree with that of strongly coupled SRS. The growth rate roughly agree with those of SRS later in time. We also point out that with mobile ions the anti-Stokes sideband is six times larger in intensity in the forward light spectrum. The absorption is measured by monitoring the Poynting flux in the $x$ direction as a function of $x$. In 1D the absorption was between 15-20% and the reflectivity was between 10-15%. At a similar time in the 2D runs the reflectivity was similar while the Poynting flux leaving the right hand boundary was less by 33%. Part of this discrepancy is due to the $y$ component of the Poynting flux. Before the competing phenomena, we are about to discuss, occur in the 2D runs, the distribution function still was approximated by a two temperature Maxwellian with a $T_i = 80$ keV and $T_{\text{superhot}} = 250$ keV. With fixed ions the distribution function is not represented by a Maxwellian.

Although, as was just discussed, there are both qualitative and quantitative differences in the behavior of SRS, by far the most prominent difference between the 1D and 2D results is the appearance of competing 2D phenomena. In the runs presented here a simple and clear picture is observed. First, the anisotropic heated electron distribution function drives the Weibel instability. Second, the electron filamentation from the Weibel instability caused density striations which filament the incident radiation. This even occurs with fixed ions. Last, toward the end of the run, density depressions (bubbles) form which generate fast ions. We will now briefly discuss each of these processes.

The free energy source that drives the Weibel instability comes from an anisotropic electron distribution function. In these simulations the anisotropic distribution function arises from the trapped electrons that are concomitant with RBS-RSS. In the fluid description the disper-
FIGURE 5. A contour plot of the transverse Electric Field at $t = 780 \omega_p^{-1}$. The light has filamented. The pattern follows closely that of the vector potential in figure 4.
FIGURE 6. Ion phase space plots at $t = 800 \omega_p^{-1}$.

(a) The $x$-$y$ phase space showing the hole from the bubble and the density striations from the filamentation.

(b) The $P_y$-$x$ and $P_y$-$y$ phase spaces show the generation of fast ions.