Kinetic Theory of Electron-Plasma and Ion-Acoustic Waves in Nonuniformly Heated Laser Plasmas

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Using Fokker-Planck simulations, we have studied the evolution of different charge state plasmas heated by lasers having transverse spatial modulations (speckle patterns) and hot spots. The kinetic response of the plasma is computed using the resulting strongly non-Maxwellian electron velocity distribution functions. Significant reductions in the electron plasma wave Landau damping rates and large modulations in the local ion acoustic frequencies are found which impact the behavior of all parametric instabilities in such plasmas. Various experimental consequences are given. [S0031-9007(98)05612-9]

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When a high intensity laser illuminates a plasma, large scale nonuniformities in the laser spatial profile will cause differential heating in the plasma, giving rise to steep temperature gradients, nonlocal heat transport, heat flux inhibition [1], and non-Maxwellian inverse bremsstrahlung heating especially in laser hot spots [2,3]. Laser spatial profile nonuniformities can contribute to the dephasing of three wave parametric instabilities in the usual way [4]. But the effect of these nonuniformities on the *background plasma* and kinetic characteristics of waves, which then affect instabilities in a fundamental way, has, in the past, been largely ignored [5]. We begin to address that in this Letter by examining the behavior of plasma waves using velocity distribution functions (VDFs) obtained from Fokker-Planck (FP) simulations of nonuniformly heated large scale plasmas. Laser speckle patterns are taken into account, the resulting nonuniform heating is simulated, and their consequences on electron plasma wave (EPW) and ion acoustic wave (IAW) properties are calculated by solving the appropriate kinetic dispersion relations. Significant changes in the properties of these waves are uncovered which shed light on some key puzzles in recent laser-plasma interaction experiments. One concerns the stimulated Raman scattering (SRS) instability (which involves light scattering off of EPWs [6]), which is observed from densities that are too low were the VDFs to have been Maxwellian at the measured temperature [7]. Similarly, instabilities involving ion waves [8] seem to be suppressed at high densities in the strong ion wave damping limit and stimulated Brillouin scattering (SBS) is observed to be anticorrelated with SRS [9]. In addition, high Z plasmas have been observed to exhibit SRS levels that depend strongly on ion wave characteristics [10]. In those experiments, the potential for Langmuir decay instability (LDI) to saturate SRS was brought into question and resolved by invoking reduced damping rates of EPWs via the mechanism discussed in this Letter [5,10]. Moreover, crossed beam SBS and SRS gains have been shown to be anomalously low with randomly displaced frequency peaks [11]. We will show that this is to be expected whenever the instabilities occur in laser hot spots, wherein the frequencies and damping rates of the waves are modified due to non-Maxwellian VDF effects.

The use of random phase plates (RPP) was pioneered over a decade ago in laser plasma interaction experiments [12], and they have been used ever since. RPPs are meant to replace unpredictable and unwarranted large scale variations in laser intensity with a statistically well defined spiky interference or speckle pattern [13]. Given any such nonuniform laser illumination profile, it is important to obtain the resulting electron VDFs from a FP calculation as the plasma is heated to inertial confinement fusion (ICF) relevant temperatures of 2 or 3 keV. We have done this with both the FPI [3] and SPARK [14] codes in large 1D simulations and smaller 2D boxes for comparison. We shall concentrate on the set of comprehensive 1D runs using FPI in this Letter and report on 2D results elsewhere. These simulations used a lateral cut across a 0.35 μm wavelength RPP beam which was 211 μm wide. The plasma had two side, or "moat," regions of the same width as the beam, all held at a density of a tenth critical. The ionization states were low to moderate ($\bar{Z} = \langle Z^2\rangle/\langle Z\rangle = 5, 10, 20$). The angular dependence of the VDF is expanded in Legendre polynomials in FPI up to order three. Inspection of the values showed that the $|f_2|/f_0$ ratio was below one in all regions where f_0 was not vanishingly small. Only f_0 is used in the present analysis. Beyond each edge of the 211 μm wide beam, the intensity was allowed to fall off linearly over 73 microns, and then there was a 139 μm unheated region before reaching the simulation box boundaries, which were maintained at the initial temperature of 300 eV.

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These large unheated regions essentially eliminate the effects of boundaries on the transport physics within the beam, since hot electrons generated in hot spots are quickly transported into the large cooler regions surrounding the beam before being absorbed at the boundaries (and reemitted with an equivalent flux at the prescribed wall temperature).

In order to show the resulting VDFs, we resort to the shorthand of a set of super-Gaussian functions which were first introduced by Dum in a number of different plasma physics contexts [15], and which were found to be ideal for the description of quasi-steady state, uniform-intensity illumination, laser-plasma heating, and transport simulations by Matte using his FPI code [2,3]. These Dum-Langdon-Matte (DLM) VDFs may be written in the form

$$f_e = C(n)\,\frac{N_{e0}}{v_e^3}\exp\left[-\left(\frac{|v|}{\alpha_e v_e}\right)^n\right], \tag{1}$$

where $v_e^2 = T_e/m_e$, and the constant $\alpha_e = [3\Gamma(3/n)/\Gamma(5/n)]^{1/2}$ is chosen to ensure the proper definition of temperature in terms of the second moment of the 3D distribution function: $\langle v^2 \rangle = 3v_{\rm th}^2$. The normalization prefactor is $C(n) = [1/(4\pi\alpha_e^3)][n/\Gamma(3/n)]$, which ensures that the zeroth moment of the 3D distribution function is the density N_{e0}. In the standard theory of non-Maxwellian inverse bremsstrahlung heating [2,3], as the laser intensity is increased, the exponent n increases from the Maxwellian limit of $n = 2$ to the limit where electron-electron collisions are entirely negligible, $n = 5$. These distribution functions will have increasingly more flattened cores and depleted tails. In fact, for uniform laser illumination cases, Matte [3] has obtained the connection between the exponent n and parameters that characterize the laser-plasma system. With the laser intensity I defined in units of 10^{15} W/cm^2, laser wavelength λ_0 in units of 0.35 μm, and the electron temperature T_e in keV, the conversion is $\overline{Z}I_{15\,{\rm W/cm^2}}\lambda^2_{0,0.35\,\mu{\rm m}}/T_{e\,{\rm keV}} = 44.29[(n-2)/(5-n)]^{1.381}$.

Since this result neglects the nonlocal heat transport that accompanies spatially nonuniform non-Maxwellian inverse bremsstrahlung heating, we would expect the Matte formula to slightly overestimate the proper DLM exponent n at the very centers of the hot spots and to severely underestimate the non-Maxwellianness everywhere else in the illuminated region. New FP simulations using RPP beam patterns were performed precisely in order to overcome these limitations, which a direct reliance on DLMs and the Matte formula would cause [5,16]. The resulting inferred DLM exponents n from the Ca simulations and those predicted by Matte's formula are shown in Fig. 1 together with the laser intensity distribution and the (FP simulation obtained) temperature profile normalized to the average temperature in the illuminated region. Figure 2 shows the damping rate of EPWs in plasmas whose e^- VDFs are given by the FP codes directly, normalized to that of EPWs in a Maxwellian plasma at the same density and at the same average temperature (inside the illuminated region). The electron susceptibility is given by [6]

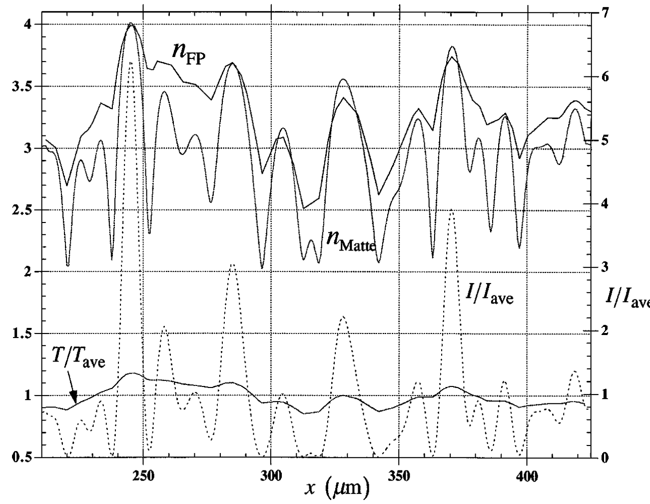

FIG. 1. The DLM exponent n and the temperature (normalized to the average temperature in the illuminated region, $T_{\rm ave} = 2.26$ keV) extracted from FPI simulations of a Ca plasma at a tenth critical density vs lateral position x in an $f/4$ RPP laser beam whose intensity distribution is plotted as $I/I_{\rm ave}$, where $I_{\rm ave} = 2 \times 10^{15}$ W/cm^2. Also shown are DLM exponents inferred from the Matte formula which underestimates the degree of non-Maxwellianness everywhere except at the centers of the hot spots.

$$\chi_e = \frac{\omega_{p_e}^2}{N_{e_0}k^2\overline{f}_e}\int \frac{\mathbf{k}\cdot\partial f_e/\partial \mathbf{v}}{(\omega - \mathbf{k}\cdot\mathbf{v})}\,d\mathbf{v} \tag{2}$$

$$= \frac{1}{A}\,\frac{1}{k^2\lambda_{\rm De}^2}[1 + \zeta_0 I(\zeta_0)], \tag{3}$$

where $\zeta_0 = (\omega/\omega_{pe})/(k\lambda_{\rm De})$, $A = N_{\underline{e_0}}/(2\pi\overline{f}_e)$, N_{e_0} is the 3D average of the e^- VDF, and $\overline{f}_e$ is its 1D average. The Hilbert transform of the normalized VDF is defined via the integral $I(\zeta_0) = [\int d\zeta\, f_e(\zeta)/(\zeta - \zeta_0)]/\overline{f}_e$. Solving $1 + \chi_e = 0$ gives us the complex frequencies of damped EPWs. The resulting damping rates for a Ca plasma at an average temperature of 2.26 keV are shown in Fig. 2. Note the order of magnitude reduction in EPW damping rates compared to those in a Maxwellian plasma at values of $k\lambda_{\rm De} \approx 0.35$ that typically arise in experiments.

The impact of non-Maxwellian e^- VDFs on IAWs can be seen by noting the factor A which renormalizes $k^2\lambda_{\rm De}^2$ in Eq. (3). It acts to boost the effective electron temperature that enters the definition of the frequency of an IAW: $\omega_{\rm IAW}^2 = Ac_s^2k^2$. The reduced number of slow electrons available to shield the ions causes this IAW frequency increase over that of a Maxwellian plasma. For DLMs, we have calculated this boosting factor analytically to be [5] $A(n) = 3[\Gamma(3/n)]^2/[\Gamma(1/n)\Gamma(5/n)]$. In Fig. 3, we plot the actual A factor calculated using the VDFs obtained from the FP simulations, multiplied by the ratio of the spatially varying temperature obtained from the FP runs

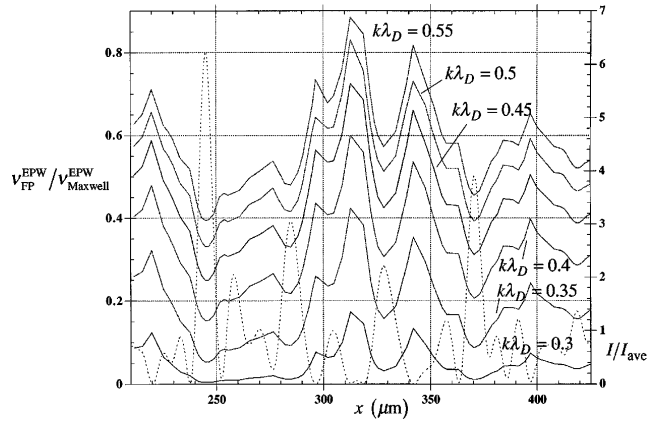

FIG. 2. EPW damping rates which are solutions of the kinetic dispersion relation using the distribution function obtained from Fokker-Planck simulations, normalized to Maxwellian plasma damping rates at the same average temperature vs lateral position x for $k\lambda_{De} = 0.35-0.55$ in steps of 0.05.

divided by the average temperature vs lateral position inside the RPP beam for CH, Ne, and Ca plasmas at a tenth critical density and an average laser intensity of 2×10^{15} W/cm^2. rms fluctuations exceeding 20% are obtained via this ion acoustic frequency spatial modulation effect due to spatially nonuniform and non-Maxwellian inverse bremsstrahlung heating. Such modulations can help explain the recent crossed beam SBS results of Kirkwood *et al.* [11], where anomalously low crossed beam gains were found with seemingly random peaks in the frequency tuning curves in the strongly damped IAW limit. Details of the interplay between this kinetic effect and that of velocity fluctuations which conspire to detune the instability will be given elsewhere [17]. However, since the two effects are complementary, this kinetic frequency shift reduces the size of velocity fluctuations (required to produce an order of magnitude lower SBS gain than in a uniform plasma illuminated by a uniform laser beam) to about 10%.

To show the effects of EPW damping reduction on parametric instabilities driven by RPP laser beams, we solved the kinetic dispersion relation of SRS [18] using the FP generated VDFs. The results are shown in Fig. 4, where we plot the ratio of SRS spatial gain rate κ_{FP} using VDFs obtained via FP simulations to those of a Maxwellian at the same temperature $\kappa_{Maxwell}$ for the Ca and Ne plasma cases. Note that more than an order of magnitude increase in SRS gain rates is obtained inside hot spots even with nonlocal heat transport which tends to smooth out the differences between the high energy portions of the e^- VDFs at different positions. In any case, they remain highly non-Maxwellian. These large gain enhancement factors allow the occurrence of SRS at low densities and at high temperatures which could simply not occur in a Maxwellian plasma. Elsewhere, non-Maxwellian VDFs will turn otherwise convective SRS into absolute instabilities which would require nonlinear mechanisms to reach saturation.

In summary, we have shown in this Letter that an order of magnitude or more increase in SRS gain rates may be expected from low density and high temperature plasmas whenever high intensity RPP beams nonuniformly heat a plasma. This suggests that Raman can grow at densities lower than expected and at temperatures higher than expected by relying on Maxwellian assumptions. We

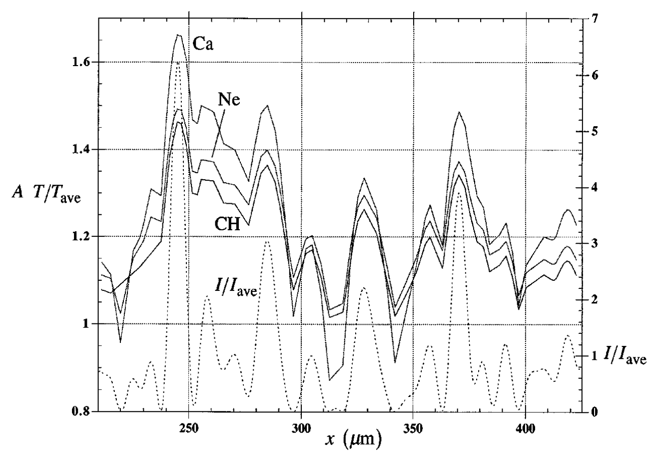

FIG. 3. The ratio of the sound speed squared using the distribution function from Fokker-Planck simulations to that of a Maxwellian plasma at the same average temperature vs lateral position x for CH, Ne, and Ca plasmas at a tenth critical density and with an average temperature of 2.26 keV. This is the A factor which boosts the IAW temperature with respect to the energy temperature, multiplied by the spatially varying temperature normalized to the average temperature: $AT_e(x)/T_{ave}$. Typically, 20% or more rms spatial variation in sound speed can be attained due to this kinetic effect.

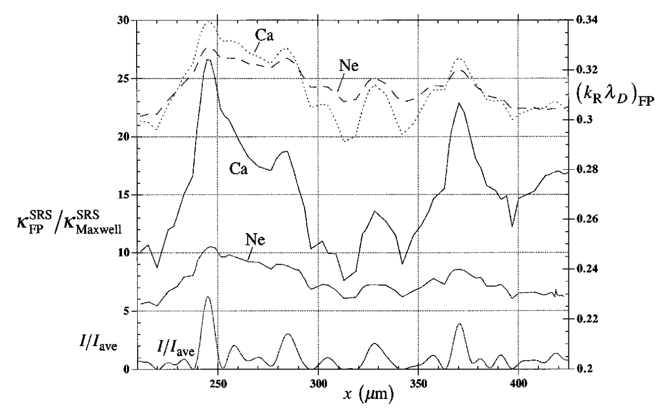

FIG. 4. The spatial gain coefficient for stimulated Raman backscattering using the distribution functions generated by Fokker-Planck simulations normalized to that of a Maxwellian plasma at the same temperature vs lateral position x for Ca ($\overline{Z} = 20$), and Ne ($\overline{Z} = 10$), plasmas at a tenth critical density and with an average temperature of 2.26 keV. Also plotted are the real frequencies of the most unstable modes (dotted and dashed curves) and the intensity profile of the RPP beam. Order of magnitude increases in gain rates over Maxwellian plasmas are obtained.

have also noted that parametric instabilities which rely on the properties of IAWs, such as SBS, LDI, and EDI [8], will be significantly detuned in the strong IAW damping limit since IAW frequencies were shown to be spatially modulated by 20% or more over length scales short compared to the interaction lengths required for significant gain [17].

We plan to report on extensions of this work next by using filamentation generated intensity profiles [19] and not just RPP ones. We have seen that, in that case, the axial extent of hot spots will be so shortened that dephasing will be substantial even for backscattering instability. This suggests that filamentation could potentially suppress SBS backscatter (SBBS), especially in the strong IAW damping limit, making SBBS more likely at lower densities (where hot spot lengths would be long) than at higher densities where filamentation would be rampant and the correlation length of hot spots would be much shorter, making the concomitant modulation frequency of IAWs even more effective in suppressing SBBS and LDI.

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