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Kinetic Scattering Effects in Laser Plasma Interactions

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Introduction Non-Maxwellian particle distributions can allow the plasma to support a variety of modes often omitted from studies of laser-plasma interactions. Such modes, which require a kinetic description of the plasma, can significantly affect the scattering of incident laser light. Both the electron acoustic wave (EAW), which can be supported by electrons trapped in a finite-amplitude wave, and the beam acoustic mode (BAM), which can be supported by drifting beam electrons, have been identified as possible longitudinal daughter waves for stimulated scattering in plasmas. These modes permit undamped oscillation at frequencies significantly lower than the electron plasma frequency ω_{pe}, and so provide an additional mechanism for stimulated Raman-like scattering. Single hot-spot experiments using the Trident laser facility have indeed observed backscatter which resembles stimulated Raman scattering, and can occur in combination with it, but arises from a lower-frequency mode with $\omega \approx 0.41\omega_{\mathrm{pe}}$ identified with the EAW[1,2]. Here we report fully nonlinear kinetic simulations[3] using a one-dimensional Vlasov-Poisson system of electrons and immobile protons, used previously[4] to model other kinetic phenomena relevant to laser-plasma interactions. These simulations demonstrate stimulated scattering both from Langmuir waves and from modes with frequencies significantly below the plasma frequency, in the range $0.6\omega_{\mathrm{pe}}$ to $0.8\omega_{\mathrm{pe}}$. The importance of kinetic effects in saturating the conventional SRS component is also highlighted. For example, in some of our simulations, an initial burst of stimulated Raman scattering saturates via trapping of electrons, thereby providing an environment in which EAWs can grow; stimulated scattering from these EAWs is then seen later in the simulation. There are physical parallels with the role of energetic-particle-supported modes in magnetic fusion plasmas, which include: coupling to external drivers; nonlinear cascades; and diagnostic information.

Results Both BAMs and EAWs can be considered as Vlasov-Poisson modifications to a Maxwellian particle distribution that result in flattening about a particular velocity. In the case of the EAW[5], the modification is an odd function about v_p given by

$$f_1(v) = \partial_v f_0\big|_{v_p} (v - v_p) \exp\left(\frac{-(v - v_p)^2}{\Delta v^2}\right)$$

or similar, with an effective density of zero in the sense that $\int f_1 dv = 0$. This modifies the solutions to the Landau integral

$$\frac{1}{2(k\lambda_d)^2} \int_{-\infty}^{+\infty} \frac{\partial_v f(v)}{v - \omega/(kv_T)} dv$$

in the conventional Langmuir dispersion relation to allow the propagation of EAWs. However, the BAM is supported by a beam added to the distribution at $v = v_b$. This beam is described by a function f_2 which is even about v_b and has a finite associated density given by $\int f_1 dv = n_2$. Rather than modifying the Landau solution, this beam admits a whole new branch of solutions.

The Vlasov solver introduced by Arber and Vann[6] and expanded in later work[3,4] was adapted for a system with a continuous, sinusoidal, EM driver and open boundaries. Any charge flowing past the system boundaries is assumed to reside on a 'charged plate', external to the system. This external charge is included when calculating the electrostatic potential, in order to avoid the creation of a DC field. The electrostatic potential is found using a tridiagonal matrix inversion, which in turn is used to calculate the electrostatic field. The laser intensity I_0, electron temperature T_e and density n_e achieved[1,2] in single hot-spot experiments were approximately: $I_0 = 1.6\mathrm{x}10^{16}$ Wcm^{-2}, T_e = 350eV and $n_e = 1.2\mathrm{x}10^{20}$cm^{-3}. These imply values for the simulation parameters: incident EM wave amplitude $E_y = 0.33 m_e c\omega_{pe}/e$; frequency $\omega_0 = 5.7775\omega_{pe}$; thermal velocity $v_{Te} = 0.026c$; and density $n_e = \varepsilon_0(\omega_{pe}/e)^2 = 0.03 n_{crit}$. To minimise the charge loss from the system, a 'flat-top' density profile is used, where the density of both the electrons and the neutralising ion background drops smoothly to zero over a distance $\approx 40\ c/\omega_{pe}$ at the edges of the system. The simulation domain extends from $x = 0$ to $x = 220c/\omega_{pe}$, leaving a flat region at the centre of the simulation box approximately $x = 140c/\omega_{pe}$ in length, and from $p = -0.75 m_e c$ to $p = 0.75 m_e c$. The simulation grid has 16,384 points in x and 1,024 points in p. The simulation runs to an end time of $1200/\omega_{pe}$.

Figure 1 displays a windowed Fourier transform of the electrostatic field taken with a Hanning window of size $\approx 75/\omega_{pe}$, at the centre of the system. This shows the development of low frequency plasma waves after $t = 600/\omega_{pe}$. In the initial SRS burst, starting at $t = 450/\omega_{pe}$ the EM driver at ω_0 scatters from a Langmuir wave at $\omega_1 = 1.06\omega_{pe}$, $k = 0.27/\lambda_D$, $v_p = 3.93v_{Te}$, to produce reflected light at a frequency $\omega_2 = 4.72\omega_{pe}$. This instability saturates via the trapping of electrons.

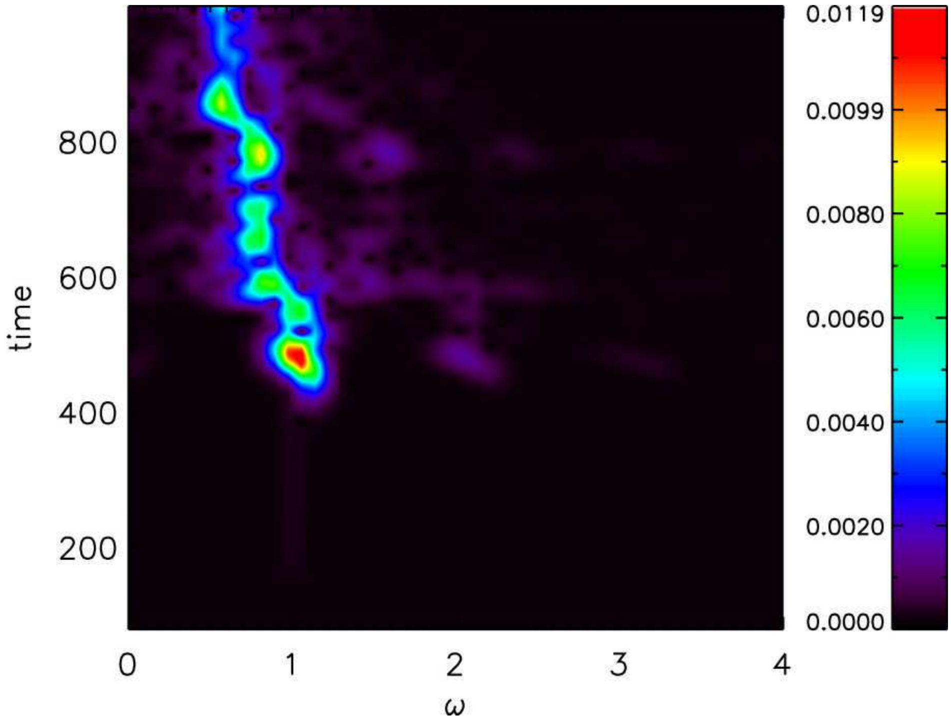

Figure 1 Windowed Fourier transform of the electrostatic field E_x at the centre of the system. An initial SRS burst saturates via the trapping of electrons, which distort the initially Maxwellian distribution and provide an environment in which waves below the plasma frequency can grow and propagate. The traces at $\omega_0 \approx 0.8\omega_{pe}$ and $\omega_0 \approx 0.6\omega_{pe}$, first appearing at $t = 600/\omega_{pe}$, represent EAWs with phase velocities at $v_p = 2.73v_{Te}$ and $v_p = 2.03v_{Te}$.

The electron distribution at late times deviates significantly from a Maxwellian. The trapping of electrons in the initial SRS burst flattens the distribution around $p = 1.5m_ec$, allowing the development of low frequency plasma waves whose trapped electrons further distort the distribution of particles. By the simulation's end, it has become clear that the plasma, and hence the modes which it supports, is not well described by linear or fluid approximations. Scattering observed in single hot-spot experiments was from EAWs with phase velocity $v_p = 1.4v_{Te}$ ($k = 0.279/\lambda_D$, $\omega = 0.41\omega_{pe}$), with a backscattered wave amplitude over a thousand times smaller than that from SRS. The amplitude of EAWs, and of the light scattered from them, is greater observed in simulations than observed experimentally. The simulations outlined here also produce EAWs with higher phase velocities than the scattered spectra from experiments indicate. These two deviations are closely related. The dispersion relation for the

EAW is dictated in part by the mode amplitude. As the EAW amplitude is increased, the dispersion relation shifts inwards, as described in previous work[3], resulting in a higher phase velocity at fixed wavenumber. Further work is required to quantify in greater depth this inconsistency between numerical and experimental results.

The simulation runtime $t = 1200/\omega_{pe}$ is equivalent to less than three picoseconds; this serves to highlight how rapid the switch from the fluid to the kinetic regime may be, at the laser intensities considered here. As laser intensities increase, the kinetic effects discussed here will become more critical to the understanding of the associated laser-plasma interaction physics.

Conclusions A plasma with a non-Maxwellian velocity distribution can accommodate electron plasma waves with frequencies below the plasma frequency. These may be supported by beams (BAM) or trapping (EAW). Laser scattering off such modes has been observed experimentally. Here we have demonstrated numerically that scattering off low frequency plasma waves does occur, but that the distribution function is so far from Maxwellian that it may not be possible to determine if these are BAM[7] or EAW modes. The deviation from the Maxwellian due to transient beam-like structures has also been observed in other simulations[8]. The amplitude of the reflected EM wave is also greater than that observed experimentally, which may be due to the 1D nature of these simulations.

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