On the Role of Electron Acoustic Waves and Beam Acoustic Modes in Laser Backscatter from Plasmas

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\textbf{Abstract.} 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 $\omega_{pe}$, 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 $\omega = 0.41\omega_{pe}$ identified with the EAW. Here we report fully nonlinear kinetic simulations using a one dimensional Vlasov-Maxwell system of electrons and immobile protons, used previously 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 $0.6\omega_{pe}$ to $0.8\omega_{pe}$. 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. We also outline work currently underway to extend the treatment to two spatial dimensions, where lateral transport and scattering losses may effect the formation and evolution of trapped electron structures, such as the EAW and BAM.

1. Introduction

Non-Maxwellian particle distributions can allow the plasma to support a variety of modes which require a kinetic description of the plasma and 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 $\omega_{pe}$, 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 $\omega = 0.41\omega_{pe}$ identified with the EAW. Here we report fully nonlinear kinetic simulations using a one dimensional Vlasov-Maxwell system of electrons and immobile protons, used previously 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 $0.6\omega_{pe}$ to $0.8\omega_{pe}$. 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. We also outline work currently underway to extend the treatment to two spatial dimensions, where lateral transport and scattering losses may effect the formation and evolution of trapped electron structures, such as the EAW and BAM.
plasma frequency $\omega_{pe}$, and so provide an additional mechanism for stimulated Raman-like scattering. Single hot-spot experiments have observed backscatter which resembles stimulated Raman scattering, and can occur in combination with it, but arises from a lower-frequency mode with $\omega \approx 0.41 \omega_{pe}$ 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 to model other kinetic phenomena relevant to laser-plasma interactions [4]. These simulations demonstrate stimulated scattering both from Langmuir waves and from modes with frequencies significantly below the plasma frequency, in the range $0.6 \omega_{pe}$ to $0.8 \omega_{pe}$. 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.

2. Results
Both BAMs and EAWs can be considered as modifications to a Maxwellian particle population 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

$$\int f_1 dv = 0$$

This modifies the solutions to the Landau integral

$$\frac{1}{2k^2(\lambda_d)^2} \int_{-\infty}^{\infty} \partial v f(v) dv - \omega_0(kv_T)$$

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 an associated density given by

$$\int f_2 dv = n_2$$

Rather than modifying the Landau solution, this beam admits a whole new branch of solutions.

A 1D EM Vlasov solver, based on the electrostatic solver introduced in Ref. [6] was used with a continuous, sinusoidal, EM driver and open boundaries. The laser intensity $I_0$, electron temperature $T_e$ and density $n_e$ achieved in single hot-spot experiments [1,2] were, approximately: $I_0 = 1.6 \times 10^{10}$ W cm$^{-2}$, $T_e = 350$ eV, $n_e = 1.2 \times 10^{20}$ cm$^{-3} = 0.03 n_c$. These imply values for the simulation parameters (incident EM wave amplitude $E_r$ and frequency $\omega_0$, thermal velocity $v_T$, and density $n_e$) of $E_r = 0.33m_ec\omega_{pe}/\epsilon$, $\omega_0 = 5.7775\omega_{pe}$, $v_T = 0.026c$, $n_e = 1 \times 10^6 \epsilon_0/e^2 = 0.03 n_c$. A ‘flat-top’ density profile is used, where the density of both electrons and the neutralising ion background drops smoothly to zero over a distance $\sim 40c/\omega_{pe}$ 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 $x \sim 140c/\omega_{pe}$ in length, and from $p = -0.75m_ec$ to $p = 0.75m_ec$. The simulation grid has 16,384 points in $x$ and 1,024 points in $p$.

Figure 1 displays a windowed Fourier transform of the electrostatic field taken with a Hanning window of size $\sim 75/\omega_{pe}$, 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 $\omega_0$
scatters from a Langmuir wave at $\omega_1 = 1.06 \omega_{pe}$, $k = 0.27/\lambda_D$, $v_p = 3.93 v_T$, 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 $\omega \approx 0.8 \omega_{pe}$ and $\omega \approx 0.6 \omega_{pe}$, first appearing at $t = 600/\omega_{pe}$, represent EAWs with phase velocities at $v_p = 2.73 v_T$ and $v_p = 2.03 v_T$.

Figure 2. (a) Surface plot of the electron distribution near the centre of the system at $t = 500/\omega_{pe}$. Electron trapping, visible here, is responsible for the saturation of the Raman instability and the creation of the electron beam in the spatially integrated distribution. (b) Spatially integrated electron distribution functions, for $t = 500/\omega_{pe}$ and $t = 1000/\omega_{pe}$ normalised to the initial Maxwellian distribution. The trapping of electrons in the Langmuir wave driven by SRS temporarily creates a beam structure. The collapse of this structure is responsible in part for the formation of a broad plateau in momentum space at late times, which supports EAWs.

Figure 2a shows the electron distribution function during the late stages of the SRS burst, when electrons have been trapped and accelerated. A beam forms in the electron distribution which is clearly visible in plots (Figure 2b). This beam could potentially support BAMs, however the beam velocity (at $v_p = 6.9 v_T$) is too high to explain the observed scattering. The trapping of electrons by the Langmuir waves driven through SRS evolves into a plateau in the electron distribution. This flattened region extends to low phase velocities allowing the development of low frequency plasma waves whose trapped electrons further distort the distribution of particles. By the later stages of the simulation, 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 $v_p = 1.4 v_T$ ($k = 0.279/\lambda_D$, $\omega = 0.41 \omega_{pe}$), 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, observed in simulations is greater 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.

Two dimensional effects may influence the evolution of scattering instabilities such as SRS & SEAS. For instance, transverse bulk motion of electrons could inhibit the formation of highly non-Maxwellian particle distributions which are required to seed SEAS. Furthermore, lateral scattering of trapped electrons could effect the non-linear saturation of parametric instabilities as could the interplay between neighboring hot-spots [7]. V2D - a 2D2P Relativistic Vlasov solver is currently under development to address these issues. The code will also be applicable in a diverse range of plasma-physics problems. Areas of interest include collisionless absorption mechanisms in ultra-short pulse laser-matter interactions (to support target heating experiments and underwrite lower-fidelity particle code results) and particle acceleration at shocks, from small scale laboratory plasmas up to supernova remnant shocks [8]. The code builds on the core algorithm of the 1D1P Vlasov solver [6] and the design is optimized throughout for use on massively parallel computing platforms.

3. 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). Scattering off such modes has been observed experimentally. Here we have demonstrated that numerically that scattering off low frequency plasma waves does occur but that the distribution function is so far from Maxwellian it may not be possible to determine if these are BAM [9] or EAW modes. The deviation from Maxwellian due to transient beam like structures has also been observed in other simulations [10]. The amplitude of the reflected EM wave is also greater than that observed experimentally which may be due to the one-dimensional nature of the model. Lateral losses of trapped electrons and interaction of neighboring hot-spots are an important consideration [11] which will be addressed by higher-dimensional simulations currently under development.

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