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Local electron acceleration by breaking Langmuir waves

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1 Introduction

Direct numerical simulations of electron dynamics in externally driven electrostatic waves have been carried out using a relativistic two-fluid one-dimensional Vlasov-Poisson code. When the driver wave has sufficiently large amplitude, ion density holes (cavitons) form. The interaction between these cavitons and other incoming Langmuir waves gives rise to substantial local acceleration of groups of electrons: fine jet-like structures arise in electron phase space. We show that these jets are caused by wave-breaking when finite amplitude Langmuir waves experience the ion density gradient at the leading edge of the holes, and are not caused by caviton burn-out.

2 The Relativistic Vlasov-Poisson System

The model used is a one dimensional relativistic Vlasov-Poisson system of electrons and protons with no magnetic field. This fully nonlinear self consistent system is governed by the Vlasov equation for the electron and ion distribution functions f_e, f_i

$$\frac{\partial f_{e,i}}{\partial t} + \frac{p}{m_{e,i}\gamma}\frac{\partial f_{e,i}}{\partial x} + q_{e,i}E\frac{\partial f_{e,i}}{\partial p} = 0, \tag{1}$$

and Poisson's equation for the electric field

$$\frac{\partial E}{\partial x} = -\frac{e}{\epsilon_0}\left(\int f_e dv - \int f_i dv\right) \tag{2}$$

The following dimensionless normalisation is adopted: $x = (c/\omega_{pe})\tilde{x}$, $t = (1/\omega_{pe})\tilde{t}$ and $E = (\omega_{pe}cm_e/e)\tilde{E}$, and all simulations use a mass ratio $M_r = m_i/m_e = 100$. The Vlasov-Poisson system is solved using a relativistic version of the code detailed in [1]. The initially Maxwellian distribution functions f_e, f_i are calculated on a fixed Eulerian grid periodic in x and quasi-infinite in p, and the solver is split into separate spatial and velocity space updates [2]. These updates are one dimensional, constant velocity advections using the piecewise parabolic method [3]. A large amplitude external driving field $\tilde{E}_d = \tilde{E}_0 \sin(\tilde{k}\tilde{x})\sin(\tilde{\omega}_0\tilde{t})$ is added to the self consistent electric field found from Poisson's equation. The system is driven at resonance ($\omega_0 = \omega_{pe}$, $\tilde{\omega}_0 = 1$ in normalised units), and the intensity of the perturbations corresponds to the high quiver velocity regime $v_q^2/v_{Te}^2 > 1$, where $v_q = eE_0/m_e\omega_0$. Hence $E_0 > m_e\omega_0 v_{Te}/e$, or equivalently

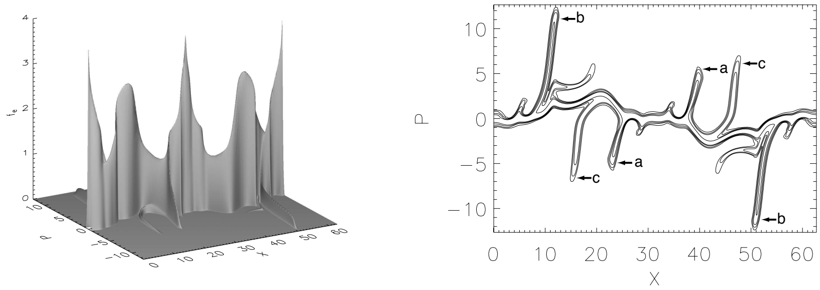

Fig. 1: f_e ***(left)*** *and contour plot of* $\log(f_e > 10^{-6})$ ***(right)*** *at time* $\tilde{t} = 40$ *for a Vlasov-Poisson system driven from* $\tilde{t} = 0$ *to* 10 *at* $\omega = \omega_{pe}$*. Fine jet-like structures in electron phase space are clearly visible, jets marked '**a**' have recently formed on the inside edges of the two cavitons. The jets marked '**b**' have formed in the same area at an earlier time and have since been advected through the system. The jets marked '**c**' are at an intermediate stage, having formed on the outside edges of the cavitons. These jets are the result of Langmuir wave-breaking at the edges of the evolving density holes.*

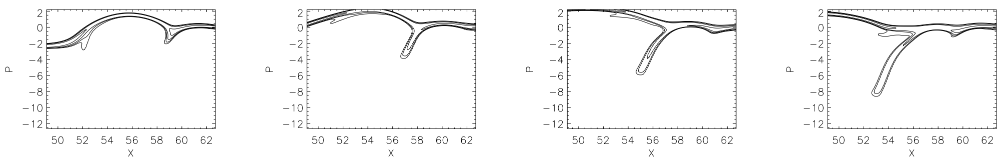

Fig. 2: *Contour plots of* $\log(f_e > 10^{-6})$ *in the region* $62 \gtrsim \tilde{x} \gtrsim 50$ *at times* $\tilde{t} = 32$ ***(far left)****,* 34 ***(left)****,* 36 ***(right)*** *and* 38 ***(far right)****. These plots show a phase space jet developing at the outside edge of the caviton at* $\tilde{x} \approx 60$*. Electrons are accelerated from a compact region of the background distribution to form the jet which extends and advects across the caviton.*

$\tilde{E}_0 > \tilde{v}_{Te}$. This driving field, similar to the perturbation used in earlier work on the modulational instability [4], is necessary to drive the formation of cavitons and is only needed during the early stages of the simulation, between $\tilde{t} = 0$ and $\tilde{t} = 10$.

3 Cavitons and Phase Space Jets

Cavitons form in response to the ponderomotive force exerted on the electrons by the driving field $\tilde{E}_d$. At later times, populations of accelerated electrons appear in the contour plots of the electron distribution function, Fig.1 (right). These are the electron phase space jets. At $\tilde{t} = 20$, ten plasma periods after the driving field has been removed, there is no evidence of jet formation. However, between $\tilde{t} = 20$ and $\tilde{t} = 40$ a series of phase space jets forms on both edges of the deepening cavitons. In Fig.1, jets are highlighted at three separate stages of evolution. There are two jets (**a**) forming on the central edges ($\tilde{x} \approx 25, 37$) of the cavitons, as well as two old jets (**b**) which have been advected across the system, crossing the cavitons on whose edges they formed. Finally, there are two intermediate jets (**c**), on the outer edges ($\tilde{x} \approx 8, 55$) of the cavitons. The most energetic electrons within these jets have energies $\approx$ 5MeV, formed from a distribution with an initial temperature of $\approx$ 0.5keV.

The appearance of these jets does not affect the development of the cavitons, which continue to deepen after the appearance of the phase space jets - this rules out caviton burn-out as an explanation for the origin of the phase space jets. The process of jet emergence is seen from the evolution of the electron distribution function, focusing on a region where a jet develops, during its early stages. Fig.2 shows a reduced section of the electron phase space, the region $50 \lesssim \tilde{x} \lesssim 62$ where the rightmost jet (labelled '**b**' in Fig.1) first appears. This region encompasses the right hand side of one of the deepening cavitons. The jet forms at the outer, right hand edge of this caviton at $\tilde{x} \approx 58$. The sequence of contour plots in Fig.2 shows that the jet then extends out from the edge of the main electron distribution, at $|\tilde{p}| \approx 2$, to momenta of $|\tilde{p}| \approx 8$ in only six plasma periods.

4 Wave Breaking

The key features of phase space jets are as follows. 1. Jets appear after $\tilde{t} \approx 20$, requiring some degree of caviton evolution. 2. Jets are not directly related to the external driver, appearing after the removal of the external driving field. 3. Cavitons persist long after the appearance of jets, indicating that jets are not associated with caviton burn-out processes. 4. Jets originate at the caviton edge. The direction of this acceleration (from the higher density region on the caviton edge towards the lower density region at its centre) indicates that phase space jets are the result of processes originating outside the caviton. From extensive numerical simulations of the system, it is clear that the breaking of Langmuir waves moving into the density gradients at the edges of the cavitons is responsible for creating the phase space jets. Figure 3 illustrates the physical process schematically. The Langmuir wave first approaches the density hole. As it moves into the region of lower density, the phase speed at the front of the wave falls. If the phase speed declines rapidly enough to overcome the effect of Landau damping (which acts to damp the incoming wave energy, and thereby prevent it from breaking), then the wave will break. This creates a strong electric field localised at the wave crest within the caviton, which accelerates electrons in its vicinity away from the background population to form phase space jets. Further numerical simulations, modelling simply the interaction of a Langmuir wave with a fixed density hole, confirm this hypothesis. Furthermore, by considering the interaction of a Langmuir wave with a linear density ramp in the fluid limit, and adding additional terms to account for the kinetic effect of Landau damping, we obtain a breaking condition

$$\tilde{E}_{L0} \exp\left(\left(\pi/2\tilde{T}_e\tilde{\eta}^2\right)^{\frac{1}{2}} \exp\left(-3/2 - 3\tilde{T}_e/2\tilde{\eta}\tilde{x}\right)\right) - \left(3/\tilde{\eta}\tilde{x}\right)^{1/2} \geq 0 \tag{3}$$

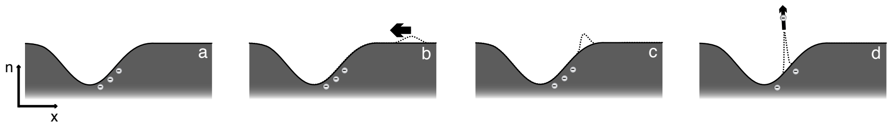

Fig. 3: *Diagrammatic representation of the process of Langmuir wave-breaking.* ***a:*** *Density hole with a few sample electrons highlighted.* ***b:*** *The crest of a Langmuir wave moves towards the density hole.* ***c:*** *As the wavefront moves down the gradient at the edge of the density hole, its phase velocity falls and the wavefront steepens.* ***d:*** *For a density hole of sufficient depth and steepness, the incoming wave breaks, forming a strong localised electric field which accelerates electrons from the inside edge of the caviton to create jets in electron phase space.*

where $\tilde{E}_{L0}$ is the initial amplitude of the Langmuir wave, $\tilde{T}_e$ is the electron temperature and $\tilde{\eta}$ is the gradient of the linear density ramp. This implies that a given Langmuir wave, of initial amplitude $\tilde{E}_{L0}$, moving down a density ramp of gradient $\tilde{\eta}$ will break, forming a jet, if (3) is satisfied for some $0 < \tilde{x} < 1/\tilde{\eta}$. Finally, by assuming that the electrons which form the jet gain their kinetic energy directly from the potential of the Langmuir wave as it breaks, one can estimate the maximum energy within a jet as well as its energy spectrum - this is supported by the results from numerical simulations.

5 Conclusions

Shortly after exposing a fully relativistic Vlasov-Poisson system to a strong external driving field, at resonance, we observe the formation of fine structures in the electron distribution function corresponding to the acceleration of a small population of electrons to high energies ($\approx$ 5MeV). These phase space jets result from the interaction of Langmuir waves (initially excited by the driving field) with cavitons formed via the ponderomotive force exerted by the external driving field. We are able to explain the origin of the small populations of electrons which form the jets, derive a necessary condition for the formation of jets starting from a basic fluid treatment, and estimate the energy distribution of electrons within the phase space jet. This process may arise everywhere that Langmuir waves move through a density gradient, and is not limited to one dimension or to caviton formation. It may therefore require consideration in laser-plasma interaction contexts spanning inertial confinement fusion and particle acceleration.

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