Plasma heating by intense electron beams in fast ignition

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Collisionless electron beam-plasma instabilities may play an important role in fast ignition[1,2]. Such beams are produced by the short high power ignition laser interacting with long scale length plasmas. Here we present results from a one dimensional Vlasov-Poisson code used to investigate the collapse of weakly relativistic beams of various initial temperatures. The simulations demonstrate that the beam-plasma instabilities drive large amplitude electrostatic waves that undergo the parametric decay instability driving electron plasma waves and much lower frequency ion acoustic waves.

Introduction

We consider the relaxation of an energetic hot electron beam propagation in a plasma. This problem is motivated by the role such beams play in plasma heating in the fast ignition scheme. Here we extend existing analytical work[3] with fully non-linear self-consistent modeling using a one dimensional Vlasov-Poisson code. This kinetic code is ideal in treating such problems since it does not suffer from resolution problems and statistical noise that sometimes limit the use of other codes. We find that initially, there is rapid growth of electrostatic waves at the electron plasma frequency. These waves reach high amplitudes and undergo parametric decay. Lower frequency ion acoustic waves are driven up by the decay of a large amplitude electron plasma wave at the same time a backwards propagating high frequency electron plasma wave is also observed, confirming the non-linear coupling. These waves are seen to be responsible for the thermalisation of the electron beam and acceleration of the tail of both electron and ion distribution functions. There is also evidence of the modulational instability, manifested in stationary solitary ion structures.

From the beam plasma dispersion relation[4] the most unstable wavenumber, parallel to the beam direction is

$$k = \frac{\omega_b}{v_b} \tag{1}$$

Where v_b is the beam velocity and

$$\omega_b = \left(\frac{e^2 n_b}{\varepsilon_0 m \gamma_b^3} \right)^{1/2} \tag{2}$$

With a growth rate given by

$$\Gamma_b = \frac{\sqrt{3}}{2^{4/3}} \omega_{pe} \left(\frac{n_b}{n_0} \right) \frac{1}{\gamma_b} \tag{3}$$

Where γ_b is the relativistic gamma at the beam velocity, n_b and n_o represent the beam and plasma number densities respectively.

As the system begins to saturate, moving into a non-linear phase, the unstable mode drives other modes parametrically from the background noise dissipating its energy in the process[5].

Energy can then be transferred from the turbulent electron plasma wave spectrum into the ion population via the modulational and parametric instabilities[3,6] which excite ion acoustic waves and drives the formation of solitary ion structures which in turn affects the long term evolution of the electron population.

A quasi-linear treatment of the beam plasma system[4,7] shows that at the end of the hydrodynamic phase, the relaxation of the beam is characterized by the quasi linear diffusion of the beam which ends with the formation of a plateau in the electron distribution function.

These effects are reproduced in our simulations. Here we detail the numerical approach adopted and summarize the principal observations, including effects not accounted for by the linear and quasi-linear treatments.

Simulations

We consider a one dimensional relativistic Vlasov-Poisson system of electrons and ions in the absence of a 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.

$$\frac{\partial f_{e,i}}{\partial t} + \frac{p}{m_{e,i}\gamma} \frac{\partial f_{e,i}}{\partial x} + q_{e,i} E \frac{\partial f_{e,i}}{\partial p} = 0 \tag{4}$$

and Poisson's equation for the electric field

$$\frac{\partial E}{\partial x} = -\frac{e}{\varepsilon_0}\left(\int f_e dp - \int f_i dp\right) \quad (5)$$

We initialise the system with periodic boundaries and a strong electron beam centred at $v_b = 0.2c$ ($p_b = 0.204m_ec$, where $p = \gamma v m_e$). The initial electron distribution is given by $f_e = f_0 + f_b$, where f_0 is a relativistic Maxwellian distribution given by

$$f_0(p) = C_0 \exp\left(\frac{-m_e}{T_e}(\gamma(p)-1)\right) \quad (6)$$

and f_b is given by

$$f_b(p) = C_b \exp\left(\frac{-m_e}{T_b}(\gamma(p-p_b)-1)\right) \quad (7)$$

where T_e denotes the background electron temperature and T_b denotes the 'temperature' of the beam in its rest frame. We fix T_e = 100eV and consider three beam temperatures, namely T_b = 10,100 and 500eV. The initial ion distribution is given by

$$f_i(p) = C_i \exp\left(\frac{-m_i}{T_i}(\gamma(p)-1)\right)$$

With temperature $T_i = 0.1T_e$. An ion mass of $m_i = 100m_e$ is used throughout.

For each initial particle distribution, $f_{0,b,i}$, the constant $C_{0,b,i}$ is calculated to ensure that there is no net charge in the system. The electron beam density n_b is chosen such that the total beam energy (directed plus thermal) in all cases is normalised to the case of $T_b = T_e$ = 100eV, $n_b = 0.1n_0$. Where n_0 is the background electron density and $n_0 + n_b = n_e$.

This system of equations is solved using a split Eulerian scheme[8]. This code has been used previously on problems of relevance to inertial fusion[9] and in considering the saturation of proton-beam instabilities in supernova remnant shocks[10,11].

A phase space resolution of (nx,np) = (4096,1024) or higher is used throughout, the length of the system is chosen to be one hundred times the most unstable wavelength, as given by the linear treatment of the beam-plasma instability.

We apply a low amplitude white-noise density perturbation to the system to seed the growth of instabilities.

Results

The results of our simulations are in broad agreement with the description of the system given in the introduction. The beam plasma instability grows initially at its most unstable wavenumber in accordance with linear theory, see Figure 1. This instability saturates non-linearly via the excitation of plasma waves and the subsequent trapping and scattering of electrons by the waves creating turbulent phase-space structures, see Figure 2. An analysis of the electrostatic field spectrum shows that the beam collapse

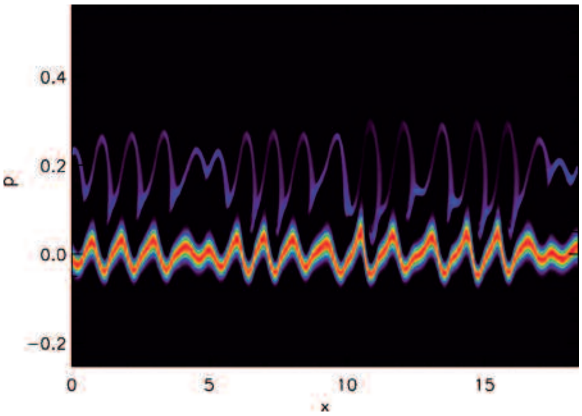

Figure 1. In the case of a cold (10eV) beam, the hydrodynamic nature of the instability at its early stages can be seen. Units in momentum space are normalised to γm_ec, units in x are normalised to c/ω_{pe}.

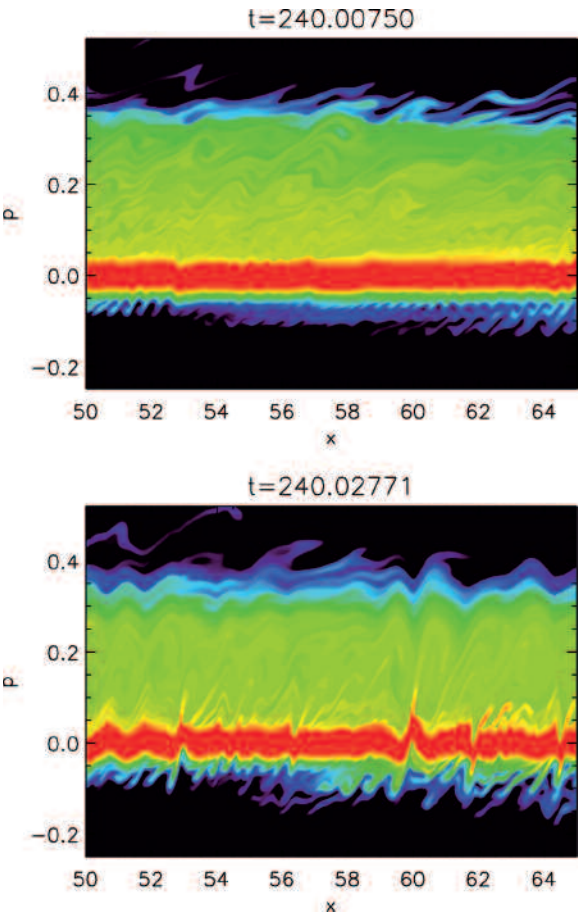

Figure 2: Contour plots of log(f_e) at time $t = 240\omega_{pe}^{-1}$ over a small section of the electron phase space for the case of the cold beam (top) and the hot beam (bottom). The collapse of the beam has created a plateau in the electron distribution, consistent with quasi-linear theory. The trapping and scattering of electrons by the broad spectrum of plasma waves generates complex phase space structures which result in the acceleration of a small fraction of the electrons to higher energies, creating 'tails' on both sides of the electron distribution. Units in momentum space are normalised to γm_ec, units in x are normalised to c/ω_{pe}.

excites principally electron plasma waves that then drive the formation of ion acoustic waves. The lowest frequency oscillations are associated with the formation of stationary ion structures.

Figure 3 shows the evolution of the spatially integrated distribution functions. At late time, in accordance with quasi-linear theory, we observe the formation of a broad plateau in the electron distribution, centred on the initial beam velocity. However, we also observe the creation of high energy tails in the electron and ion distribution functions, formed by the trapping of particles in the waves formed during the collapse of the beam. The interaction of Langmuir waves with the ion density holes driven by the modulation instability may result in the acceleration of small numbers of electrons to higher energies[9], contributing to these high energy electron populations.

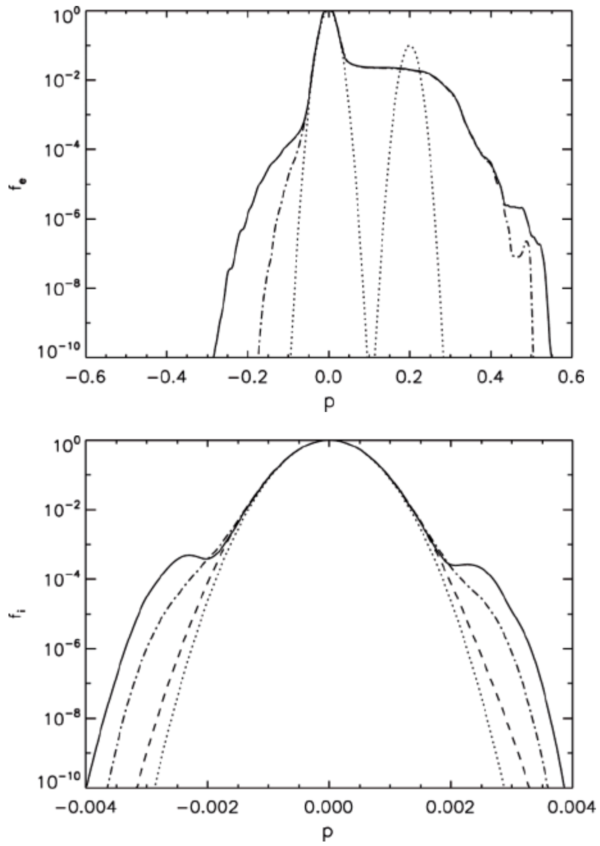

Figure 3. Spatially integrated logarithmic electron and ion distributions for the case of T_b = 100eV at t = 0 (dotted line), 240 (dashed line), 480 (dot-dashed line), 1200 (solid line). The plateau in the electron distribution formed by the relaxation of the beam is clearly visible, in addition to high energy tails on both the electron and ion distributions.

High temperature beam

For the case where the beam temperature is in excess of the background electron temperature, we observe some significant differences in the late-time evolution of the system. Long lived coherent phase space structures (see Figure 4) form at the high energy edge of the plateau of the collapsed beam. It is not, at the moment, clear what the exact mechanism driving their formation is. However, they are qualitatively similar to those observed in externally driven Vlasov-Maxwell systems[12] and they appear to be consistent with the cascade nature of the parametric instability driving up lower wavenumber modes that have higher phase velocities that can in turn accelerate electrons to energies in excess of the initial beam energy[4,11].

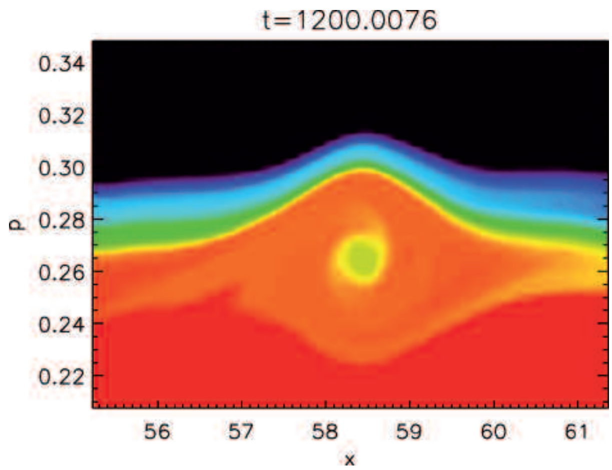

Figure 4. Trapped electron structures are observed at late time only for the 500eV beam. These phase-space holes form at the high-energy edge of the plateau created by the beam collapse.

Summary

The preliminary simulations presented here highlight the potential importance of collisionless beam-plasma instabilities to electron stopping and plasma heating in the Fast Ignitor. Consideration of the fully non-linear, self-consistent Vlasov Poisson system allows, for the first time, mechanisms revealed by previous studies[3] for the transfer of energy from the beam to the ion populations to be modeled. It is also found that the final electron energies can be greater than their initial energy in agreement with quasi-linear theory.

The presence of coherent trapped electron structures under certain conditions will be the subject of further investigation.

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