DYNAMICS OF NARROW ELECTRON STREAMS IN MAGNETIZED PLASMAS

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Abstract

The basic physics of a Buneman-like instability for electron streams with small extent perpendicular to the confining magnetic field is examined analytically and with a 2-1/2D particle-in-cell (PIC) simulation. The geometry in this scenario transforms energy associated with the parallel flow of electrons to large perpendicular electric fields in the lower-hybrid (LH) range of frequencies that cause ion acceleration and create magnetic-field-aligned density striations.

1. Overview

There are several areas of plasma research in which the dynamics of narrow electron streams embedded in a magnetized plasma play an important role. A stream is considered narrow if its transverse dimension is on the order of the larger of the electron skin-depth (c/ $_{pe}$, where c is the speed of light and $_{pe}$ is the electron plasma frequency) or the ion gyroradius. This situation may be encountered in magnetic reconnection studies [1], dynamo models [2, 3], satellite and rocket observations of depleted flux tubes in the auroral ionosphere [4, 5], structured small-scale Alfven waves, and laboratory studies of striation formation. The low frequency (below the ion cyclotron frequency, $\omega < \Omega_i$) parallel electric fields associated with these environments are capable of producing large parallel drifts, v_D, in the electron distribution function that are unstable to high frequency electrostatic modes (in the LH range).

The linear response (electrostatic potential,) of a cold plasma with an electron drift parallel to the external magnetic field $\mathbf{B_0}$ is determined from Poisson's equation

$$\frac{\partial}{\partial x} \in_{\perp} \frac{\partial}{\partial x}\Phi - k_{\parallel}^2 \in_{\parallel} \Phi = 0 \ , \qquad (1)$$

where

$$\in_{\parallel} = 1 - \left(\frac{\omega_{pi}}{\omega}\right)^2 - \left(\frac{\omega_{pe}}{k_{\parallel} v_D(x) - \omega}\right)^2 , \qquad \in_{\perp} = 1 + \left(\frac{\omega_{pe}}{\Omega_e}\right)^2 , \qquad (2)$$

and the x-coordinate gives the direction of the perpendicular variation in the drift profile. This is a good representation when the maximum drift exceeds the electron thermal velocity.

The method of matched asymptotic expansions has been used to obtain analytical results for drift profiles that decrease monotonically away from the peak, where a parabolic approximation, $v_D(x) \approx v_0(1 - x^2/2L^2)$, is made. Figure 1 depicts a typical profile along with the parallel response function. Identical to the Buneman instability, the source of the instability is in the region near the peak drift, x x_s, where the total response function is small. In the present problem, however, energy propagating away from the peak of the drift profile encounters a perpendicular resonance at x_r, where only the imaginary part of the response function is zero. The unstable mode is essentially confined to the region x x_r, leading to a large gradient in the perpendicular electric field near x_r. The analysis yields the growth rate

$$\gamma = \frac{\sqrt{3}}{2^{\frac{4}{3}}}\left(\frac{m_e}{M}\right)^{\frac{1}{3}}\omega_{pe} - \frac{v_0}{6L} \ , \tag{3}$$

where the term on the right is the nonuniform profile correction to the Buneman result (i.e., $L \to \infty$). The reduction in the growth rate appears as an effective collision frequency due to the strong effect that the resonance at x_r has on the dispersion relation.

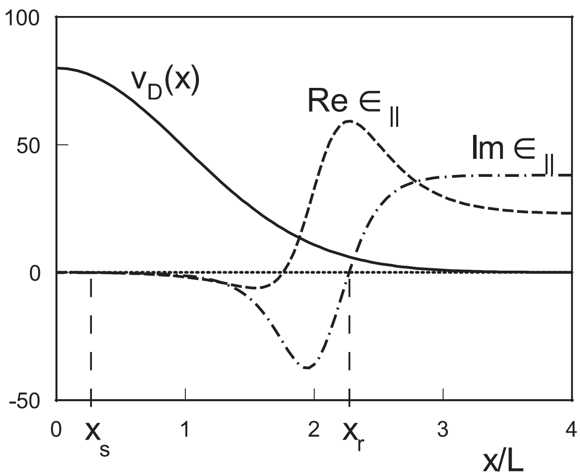

Figure 1: Spatial dependence of the parallel response function across $\mathbf{B_0}$.

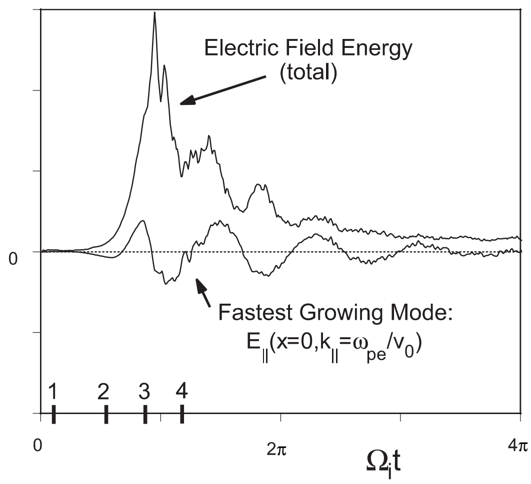

Figure 2: Time evolution of the electric field in a PIC simulation (electron drift initialized).

2. PIC Simulation

The temporal evolution of the total electric field energy and the parallel component of the fastest growing mode from a 2-1/2D PIC simulation are shown in Fig. 2. The electron distribution function is initialized with a maximum drift of $v_0 = 5\bar{v}_e$, and has a Gaussian profile perpendicular to the ambient magnetic field. The various stages of the instability are evident in the total field energy: rapid initial growth given by Eq. (3), saturation by parallel electron trapping in less than an ion gyroperiod, followed by a slow relaxation. Clear oscillations at the LH frequency are evident in the parallel electric field during the relaxation stage. This results from the rapid slowing down of the electrons during saturation, when the ions recoil to conserve parallel momentum. Because the perturbation the ions experience is localized in the direction perpendicular to the ambient magnetic field, a new feature is revealed: the nonlinear saturation of the Buneman instability leaves an imprint on the ion distribution that acts as a coherent radiator of LH waves. The spatial dependence of this effect is illustrated in Fig. 3. The initial drift profile is shown at the top of the figure for reference. Perturbations in the ion density profile (solid curve) approaching 20% of the initial density (thick dashes) are shown at a time corresponding to tick mark 4 in Fig. 2. Also shown in Fig. 3 is the time-averaged (over one LH period beginning at tick mark 4 in Fig. 2) power absorbed by the perpendicular ion distribution function. The slow decay of the LH oscillations occurring late in Fig. 2 is accounted for by this dissipation, which is seen in Fig. 3 to be peaked around the maximum gradient in the drift profile.

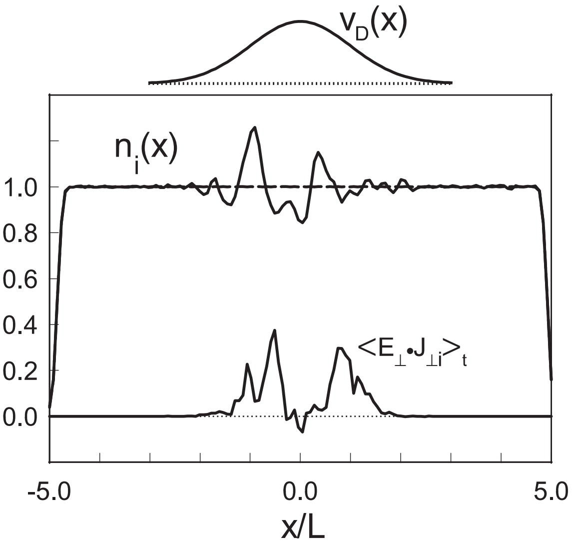

Figure 3: Instantaneous ion density and time-averaged power input to ions in a PIC simulation (electron drift initialized).

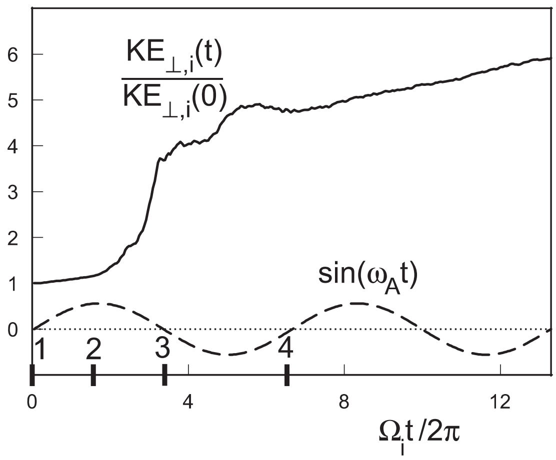

Figure 4: Temporal dependence of the perpendicular ion energy in a PIC simulation (electron drift results from low frequency $E_{\|}$).

Figure 4 shows the time dependence of the perpendicular ion kinetic energy in a PIC simulation that is identical to the initial value problem corresponding to Figs. 2 and 3, except that now the parallel electron drift is generated by a low frequency ($\omega = .15\Omega_i$) external electric field. The phase of the external field is indicated by the dashed curve and the amplitude is chosen to yield a maximum electron drift of $v_0 = 4\overline{v}_e$. Prior to tick mark 3 in Fig. 4, the increase in ion energy behaves similarly to the initial value problem, because of rapid growth of the electric field when the drift velocity first exceeds the electron thermal velocity. However during subsequent oscillations of the drive field, the parallel electron distribution function is thermalized to a new temperature that is in a quasi-equilibrium with the external drive. Therefore abrupt increases do not occur after tick mark 4 in Fig. 4, because ion acceleration after the first cycle of the external drive is due to the coherent interaction with LH oscillations that develop similarly to those seen late in Fig. 2.

2. Conclusions

Analysis of the Buneman instability resulting from a narrow current stream results in eigenfunctions with sharp perpendicular gradients. Coherent LH waves are radiated due to the perpendicular localization of the ion perturbations, and yield the steady perpendicular ion acceleration observed in the latter half of Fig. 4. This coherent absorption of LH energy occurs near sharp gradients, as indicated by the bottom curve in Fig. 3, and has been traced to spatial symmetry breaking provided by the nonuniformity in the amplitude of the perpendicular electric field [6]. These results may be useful in describing microscopic filamentary structures in an otherwise uniform magnetized plasma.

Acknowledgements

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