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Magnetic field effects on instabilities driven by a field-aligned relativistic warm electron beam and warm bulk electrons

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Instabilities driven by relativistic electron beams are being investigated due to their importance for plasma heating and electromagnetic field generation in astrophysical and laboratory plasmas [1, 2]. Particle-in-cell (PIC) simulations [3] of initially unmagnetized colliding plasmas have demonstrated the generation of strong magnetic fields and a moderate electron acceleration. The inclusion of a flow-aligned magnetic field suppresses the electromagnetic filamentation instability and PIC simulations [4, 5] have shown that the plasma dynamics turns quasi-electrostatic. To quantify the impact of the magnetic field, we have analyzed numerically a magnetized multi-fluid model that includes a kinetic pressure term [6]. This fluid model allows us to examine the beam-driven instability at all angles between the wavevector and the magnetic field vector. More accurate kinetic models typically focus only on the filamentation instability, due to the increased analytical complexity. We present here the fluid model and a growth rate map of the entire k-space for a beam Lorentz factor 4. We verify that the two-stream, mixed mode and filamentation instability belong to the same wave branch and that the magnetic field selects the fastest-growing mode. We estimate the magnetic fields required to suppress the filamentation and the mixed mode instabilities.

The fluid model

The electron number density of the bulk plasma is n_p and the magnetic field $\mathbf{B}_0 = B_0\,\mathbf{e}_z$. The density of the electron beam is n_b and its velocity $\mathbf{V}_b = V_b\,\mathbf{e}_z$ with $\gamma_b = (1-v_b^2/c^2)^{-1/2}$. The bulk electrons flow in the opposite direction with $\mathbf{V}_p = V_p\,\mathbf{e}_z$ and $\gamma_p = (1-v_p^2/c^2)^{-1/2}$. In the considered reference frame we enforce current-neutrality by demanding $\alpha V_b = -V_p$ for $\alpha = n_b/n_p$. The ions form a fixed neutralizing background.

The fluid formalism is based on Maxwell's equations and on the relativistic fluid equations

$$\frac{\partial n_j}{\partial t} - \nabla\cdot(n_j\mathbf{v}_j) = 0, \tag{1}$$

$$\frac{\partial \mathbf{p}_j}{\partial t} + (\mathbf{v}_j\cdot\nabla)\mathbf{p}_j = -e\left(\mathbf{E} + \frac{\mathbf{v}_j\times\mathbf{B}}{c}\right) - \frac{\nabla P_j}{n_j}, \tag{2}$$

where the index j is b or p, $\mathbf{p}_j = \gamma_j m_e \mathbf{v}_j$ and P_j is the partial pressure of the fluid j. The electron charge and mass are $-e$ and m_e. The fluid equations can be linearized [6]. With the scalar temperature T_j and thermal velocity $V_{tj} = \sqrt{3k_B T_j/m_e}$ we introduce the pressure gradient $\nabla P_j = m_e V_{tj}^2 \nabla n_j$. From this model, we derive a dispersion equation for wave modes with wavenumber $\mathbf{k}$ and frequency ω

$$det\left(\mathbf{I} + \mathbf{U}/x^2\right) = 0, \qquad (3)$$

where $\mathbf{I}$ is the identity matrix and the tensor elements of $\mathbf{U}$ are listed in the appendix of Ref. [6].

We define with the help of the plasma frequency $\omega_p = \left(4\pi n_p e^2/m_e\right)^{1/2}$ and electron gyrofrequency $\omega_c = eB_0/m_e c$ the normalized variables and parameters

$$\rho_b = \frac{V_{tb}}{V_b},\ \rho_p = \frac{V_{tp}}{V_b},\ \mathbf{Z} = \frac{\mathbf{k}V_b}{\omega_p},\ \Omega_B = \frac{\omega_c}{\omega_p}. \qquad (4)$$

The wavevector $\mathbf{Z}$ is confined without loss of generality to the (x,z) plane. The angle between $\mathbf{Z}$ and $\mathbf{e}_z$ is θ. The magnetization Ω_B leaves unchanged the field-aligned electron dynamics and thus the two-stream instability with $\theta = 0$. It confines the electron motion perpendicular to $\mathbf{V}_b$, which is important for the FI with $\theta = 90^\circ$. We thus expect important effects of Ω_B on the relative strengths of both instabilities and on the mixed modes with $0^\circ < \theta < 90^\circ$.

Results

The dispersion equation 3 is solved for $\gamma_b = 4$ and for three values of α and Ω_B, respectively. We examine the cases $\rho_b = \rho_p = 0$ and $\rho_b = \rho_p = 0.1$. Both cases are compared to assess the impact of the electron thermal spread. The linear growth rates as functions of α and Ω_B are shown for the cold plasma in Fig. 1. Figure 2 illustrates the linear growth rate map for the same values of α and Ω_B and for the warm plasma.

Both figures show that the density ratio α controls the importance of the FI with $Z_z = 0$ relative to the mixed mode instability and the two-stream instability with their $Z_z > 0$. Different densities of both beams shift the most unstable wave branch away from $Z_z = 0$, while we obtain the largest growth rates for $Z_z \approx 0$ if $\alpha \approx 1$.

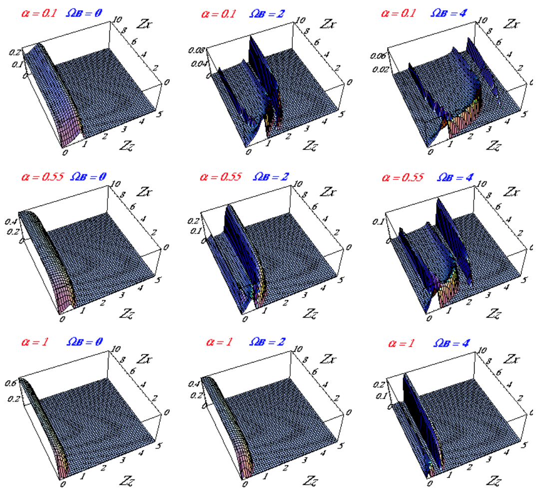

Figure 1: The growth rates in units of ω_p for the spectrum of beam-driven instabilities and for $\gamma_b = 4$. The temperatures are $\rho_b = \rho_p = 0$. The relative beam density α is varied in the vertical direction and Ω_B in the horizontal direction.

Thermal effects are negligible for waves with $Z_x \approx 0$, because $v_{tj} \ll V_b$. The electron thermal spread modifies, however, the wave growth at large Z_x. It introduces a critical Z_x, beyond which the FI with $Z_z = 0$ is suppressed. For large Z_x the Z_z of the unstable wave branches in the warm plasma increase compared to those in the cold plasma.

The reduction of the maximum growth rate by $\Omega_B \neq 0$ is more significant in the cases dominated by the FI, i.e. $\alpha = 1$, compared to the case $\alpha = 0.1$ for which the mixed / two stream modes are important. For $\Omega_B = 0$ only one unstable wave branch exists. The spectrum splits into several branches if $\Omega_B = 1$ or $\Omega_B = 4$.

A strong enough B_0 can suppress the FI [5]. Figure 3 illustrates this for $\rho_b = \rho_p = 0$ and several values of Ω_B.

The value of Ω_B that stabilizes the FI rapidly increases for increasing α and γ_b. However, the FI can be stabilized by reasonable values of Ω_B if $\alpha < 0.6$ and $\gamma_b < 4$. Such values are representative for the collisions of gamma ray burst jet fragments (internal shocks) [1].

Summary

- We have computed the growth rates of an instability driven by a relativistic electron beam from a fluid model that includes thermal effects and a flow-aligned magnetic field. A non-zero plasma temperature and magnetic field strength both suppress the electromagnetic filamentation instability.

- Moderately strong magnetic fields $\Omega_B \approx 1$ can suppress the filamentation instability for

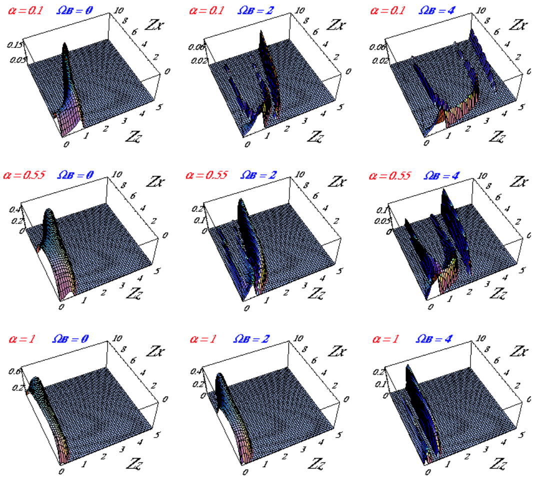

Figure 2: The growth rates in units of ω_p for the spectrum of electron beam-driven instabilities and for $\gamma_b = 4$. The temperatures are $\rho_b = \rho_p = 0.1$. The relative beam density α is varied vertically and the magnetization Ω_B in the horizontal direction.

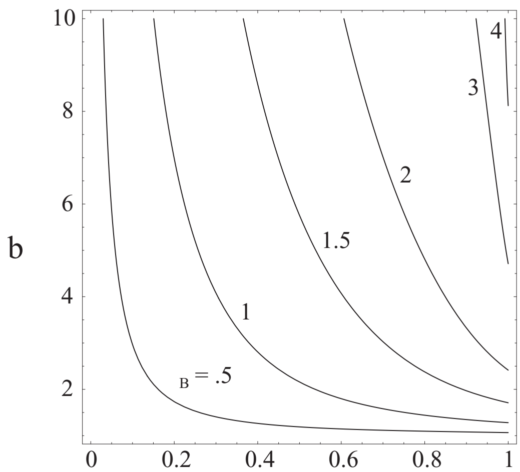

Figure 3: The curves for α and γ_b, for which the filamentation modes with $Z_z = 0$ are marginally stable. Several values of Ω_B are considered and $\rho_b = \rho_p = 0$.

plasma flow speeds and density ratios, which are realistic for internal plasma collisions (shocks) in gamma-ray bursts. Then, the electrostatic two-stream and the quasi-electrostatic mixed mode instabilities dominate the shock transition layer, rather than the typically invoked filamentation instability.

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