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Fast magnetization in counterstreaming plasmas with temperature anisotropies

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Abstract

Counterstreaming plasmas exhibits an electromagnetic unstable mode of filamentation type, which is responsible for the magnetization of plasma system. It is shown that filamentation instability becomes significantly faster when plasma is hotter in the streaming direction. This is relevant for astrophysical sources, where strong magnetic fields are expected to exist and explain the nothermal emission observed.

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1. Introduction

Presently, there is an increasing interest for a correct understanding of purely growing electromagnetic instabilities driven by a velocity anisotropy of plasma particles. [1–6]. These instabilities will release the excess of perpendicular free energy stored in the particle velocity anisotropy, whether it is a temperature anisotropy [7] or counterstreaming plasmas [8]. A substantial fraction of the kinetic energy of plasma particles is transformed by the instability and contribute to the amplification of magnetic energy [9].

Counterstreaming plasma structures are present in laboratory experiments and astrophysical systems, and they are widely investigated either to prevent the unstable modes arising in beam-plasma experiments [10,11], or to prove the existence of large scale magnetic fields in astrophysical objects [12–15].

The spontaneous magnetization of counterstreaming plasmas is associated with filamentation instability [8], which is described as a counterstreaming based electromagnetic mode purely growing in time and propagating perpendicular to the streams. Here we show that the magnetization process associated with filamentation instability can be markedly faster in counterstreaming plasmas with temperature anisotropies, namely, when plasma is hotter along the streaming direction. This fact can be decisive for the potential role of filamentation instability in producing strong quasistatic magnetic fields in astrophysical plasmas [9,13]. As long the maximum growth rate of filamentation mode is much larger than the growth rates of all other plasma instabilities (e.g., two-stream electrostatic instability), then the filamentation instability will be the fastest, and it will be the primary mechanism for the relaxation of the initial counterstreaming configuration [14].

2. Counterstreaming plasmas with temperature anisotropies

The oscillatory properties of a plasma are determined by the dielectric tensor, (ϵ), and using the linearization of Vlasov–Maxwell equations we simply get [16]

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$$(\epsilon) = \mathbf{I} + \sum_a \frac{\omega_{p,a}^2}{\omega^2} \left[\int_{-\infty}^{+\infty} d\mathbf{v}\,\mathbf{v}\frac{\partial f_{a,0}}{\partial \mathbf{v}} + \int_{-\infty}^{+\infty} d\mathbf{v} \frac{1}{\omega - \mathbf{k}\cdot\mathbf{v}} \left(\mathbf{k}\cdot\frac{\partial f_{a,0}}{\partial \mathbf{v}}\right)\mathbf{v}\mathbf{v} \right], \tag{1}$$

where the unperturbed velocity distribution function $f_{a0}(\mathbf{v})$ of the particles of sort a is normalized by $\int d\mathbf{v}\, f_{a0}(\mathbf{v}) = 1$, $\omega_{p,a} = (4\pi n_a e^2/m_a)^{1/2}$ is the plasma frequency, $\mathbf{I}$ is the unit tensor, and ω and k are respectively, the frequency and the wave number of plasma modes.

In Fig. 1 we fix the orientation for the counterstreams and the filamentation mode: the electric field, $\mathbf{E} \parallel \mathbf{v}_{1,2}$, is along the streaming direction, and the wave vector, $\mathbf{k} \perp \mathbf{v}_{1,2}$, is perpendicular to the streams. This electromagnetic mode will be solution of the following dispersion equation

$$\frac{k^2c^2}{\omega^2} = \epsilon_{yy} \tag{2}$$

with ϵ_{yy} given by (1), and c is the speed of light in vacuum.

For the sake of simplicity, we assume that the counterstreams are symmetric with equal intensities, and moving with the same velocities, $|v_1| = v_2 = v_0$. Moreover, the effect of ions is minimized to a positive background, and the electron plasma counterstreams are assumed to be homogeneous, and charge and current neutralized.

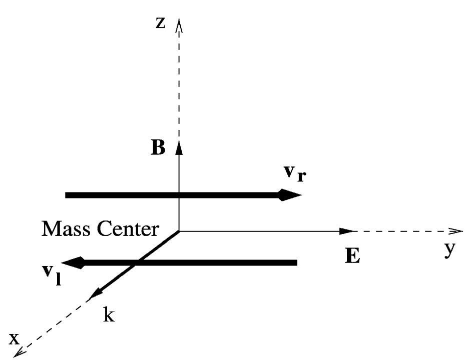


Fig. 1. Two counterstreaming plasmas and the electromagnetic filamentation mode with fields **E** and **B**, and the wavevector **k** perpendicular to the streams.

2.1. Moderate thermal effects

We first suppose that only one of the counterstreaming plasmas exhibits a temperature anisotropy of a bi-Maxwellian type, i.e. with two characteristic thermal velocities, $v_{\mathrm{th},x} = v_{\mathrm{th},z} = v_{\mathrm{th}} < v_{\mathrm{th},y}$, and the other one is monochromatic (cold)

$$f_0(v_x, v_y, v_z) = \frac{1}{2\pi^{3/2} v_{\mathrm{th}}^2 v_{\mathrm{th},y}} e^{-(v_x^2+v_z^2)/v_{\mathrm{th}}^2 - ((v_y+v_0)^2)/v_{\mathrm{th},y}^2} + \frac{1}{2}\delta(v_x)\delta(v_y - v_0)\delta(v_z). \tag{3}$$

We substitute (3) in (1), and then for dispersion relation (2) we find

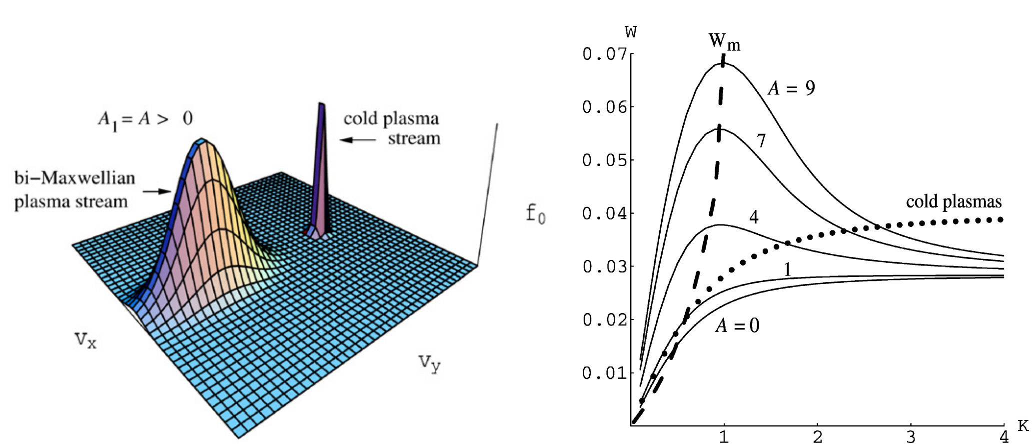
$$\frac{k^2c^2}{\omega^2} = 1 - \frac{\omega_{pe}^2}{2\omega^2}\left(1 + \frac{k^2v_0^2}{\omega^2}\right) - \frac{\omega_{pe}^2}{2\omega^2}\left\{1 + \left[\frac{1}{2}(A+1) + \left(\frac{\beta_0}{\beta_{\mathrm{th}}}\right)^2\right] Z'\left(\frac{\omega}{kv_{\mathrm{th}}}\right)\right\}, \tag{4}$$

where $\beta_{\mathrm{th}} = v_{\mathrm{th}}/c$, $\beta_0 = v_0/c$, and $Z'(f)$ is the derivative of the well-known plasma dispersion function [17]

$$Z(f) = \pi^{-1/2} \int_{-\infty}^{\infty} dx \frac{\exp(-x^2)}{x - f}, \quad f = \frac{\omega}{kv_{\mathrm{th}}}. \tag{5}$$

We assume that plasma is hotter in the streaming direction, $v_{\mathrm{th},y} > v_{\mathrm{th}}$, which defines here a positive temperature anisotropy $A_1 = A = (v_{\mathrm{th},y}/v_{\mathrm{th}})^2 - 1 > 0$. In this case the instability is driven equally by the counterstreaming motion of plasma and by the temperature anisotropy of plasma particles, and therefore we should achieve an enhancing effect for the growth rates of filamentation mode.

The aperiodic solutions of (4), $\Im(\omega) = \Omega = \Omega(k)$ ($\Re(\omega) = 0$), are plotted in Fig. 2(b) with solid lines for different val-



(a) (b)

Fig. 2. (a) Schematic representation for the distribution functions of two counterstreaming plasmas: one is assuming cold, and the other one with a two-temperatures anisotropy; (b) The growth rates of filamentation mode (solid lines) for $\beta_{\mathrm{th}} = 0.1$, $\beta_0 = 0.04$, and different values of thermal anisotropy: $A = 9, 7, 4, 1, 0$. The growth rates are also plotted for two cold counterstreaming plasmas (dotted line). The dashed line represents the *locus* of the maximum growth rates. The coordinates are scaled as $W = \Omega/\omega_{pe}$ and $K = kc/\omega_{pe}$.