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Interplay of Kinetic Plasma Instabilities

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1. Introduction

Undulatory phenomena are probably among the most fascinating aspects of our existence. It is well known that plasma is the most dominant state of ionized matter in the Universe. Moreover, it can excite and sustain any kind of oscillatory motion, acoustic or electromagnetic (light) waves. A realistic perspective upon the dynamics of space or laboratory plasmas reveals a constant presence of various kinetic anisotropies of plasma particles, like beams or temperature anisotropies. Such anisotropic plasma structures give rise to growing fluctuations and waves. The present chapter reviews these kinetic instabilities providing a comprehensive analysis of their interplay for different circumstances relevant in astrophysical or laboratory applications.

Kinetic plasma instabilities are driven by the velocity anisotropy of plasma particles residing in a temperature anisotropy, or in a bulk relative motion of a counter streaming plasma or a beam-plasma system. The excitations can be electromagnetic or electrostatic in nature and can release different forms of free energy stored in anisotropic plasmas. These instabilities are widely invoked in various fields of astrophysics and laboratory plasmas. Thus, the so-called magnetic instabilities of the Weibel-type (Weibel; 1959; Fried; 1959) can explain the generation of magnetic field seeds and the acceleration of plasma particles in different astrophysical sources (e.g., active galactic nuclei, gamma-ray bursts, Galactic micro quasar systems, and Crab-like supernova remnants) where the nonthermal radiation originates (Medvedev & Loeb; 1999; Schlickeiser & Shukla; 2003; Nishikawa et al.; 2003; Lazar et al.; 2009c), as well as the origin of the interplanetary magnetic field fluctuations, which are enhanced along the thresholds of plasma instabilities in the solar wind (Kasper at al.; 2002; Hellinger et al.; 2006; Stverak et al.; 2008). Furthermore, plasma beams built in accelerators (e.g., in fusion plasma experiments) are subject to a variety of plasma waves and instabilities, which are presently widely investigated to prevent their development in order to stabilize the plasma system (Davidson et al.; 2004; Cottril et al.; 2008).

2. Nonrelativistic dispersion formalism

Plasma particles (electrons and ions) are assumed to be collision-less, with a non-negligible thermal spread, and far from any uniform fields influence, $\mathbf{E}_0 = 0$ and $\mathbf{B}_0 = 0$. This assumption allows us to develop the most simple theory for the kinetic plasma instabilities, but the results presented here can also be extended to the so-called high-beta plasmas (where beta corresponds to the ratio of the kinetic plasma energy to the magnetic energy) since recent analysis has proven that these instabilities are only slightly altered in the presence of a weak ambient magnetic field (Lazar et al.; 2008, 2009b, 2010).

We here investigate small amplitude plasma excitations using a linear kinetic dispersion formalism, based on the coupled system of the Vlasov equation and the Maxwell equations. The standard procedure starts with the linearized Vlasov equation (Kalman et al.; 1968)

$$\frac{\partial F_a}{\partial t} + \mathbf{v} \cdot \frac{\partial F_a}{\partial \mathbf{r}} = -q_a [\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c}] \cdot \frac{\partial F_{a,0}}{\partial \mathbf{v}}, \tag{1}$$

where $F_a(\mathbf{r}, \mathbf{v}, t)$ denotes the first order perturbation of the equilibrium distribution function $F_{a,0}(\mathbf{v})$ for particles of kind a. The unperturbed distribution function is normalized as

$$\int_{-\infty}^{\infty} d\mathbf{v} \, F_{a,0}(\mathbf{v}) = 1, \tag{2}$$

and is considered to be anisotropic (the free energy source), implying that

$$\frac{\partial F_{a,0}(\mathbf{r}, \mathbf{v}, t)}{\partial \mathbf{v}} \nparallel \mathbf{v} \tag{3}$$

and the non-vanishing term

$$(\mathbf{v} \times \mathbf{B}) \cdot \frac{\partial F_{a,0}}{\partial \mathbf{v}} \neq 0, \tag{4}$$

becomes responsible for the unstable solutions (Davidson et al.; 1972). Ohm's law defines the current density, $\mathbf{J}$, and the conductivity tensor, $\tilde{\sigma}$, by

$$\mathbf{J} \equiv \tilde{\sigma} \cdot \mathbf{E} = \sum_a q_a \int_{-\infty}^{\infty} d\mathbf{v} \mathbf{v} F_a(\mathbf{r}, \mathbf{v}, t), \tag{5}$$

and using Maxwell's equations

$$\nabla \times \mathbf{B} = \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t} + \frac{4\pi}{c} \mathbf{J}, \tag{6}$$

$$\nabla \cdot \mathbf{B} = 0, \tag{7}$$

$$\nabla \times \mathbf{E} = -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t}, \tag{8}$$

$$\nabla \cdot \mathbf{E} = 4\pi\rho = 4\pi \sum_a q_a \int_{-\infty}^{\infty} d\mathbf{v} F_a(\mathbf{r}, \mathbf{v}, t), \tag{9}$$

we find the solution of Vlasov equation (1) to be

$$F_a = -\frac{iq_a}{\omega}\left(\mathbf{E} + \frac{\mathbf{v}\cdot\mathbf{E}}{\omega - \mathbf{k}\cdot\mathbf{v}}\mathbf{k}\right)\cdot\frac{\partial F_{a,0}}{\partial\mathbf{v}}. \tag{10}$$

Here, we examine large-scale spatial and temporal variations in the sense of Wentzel-Kramer-Brillouin (WKB) approximation and treat plasma wave perturbations as a superposition of plane waves in space (Fourier components) and harmonic waves in time (Laplace transforms). Thus, the analysis is reduced to small amplitude excitations with a sine variation of the form ~ $\exp(-i\omega t + \mathbf{k} \cdot \mathbf{r})$. Since we consider an infinitely large, homogeneous and stationary plasma, we choose the wave-number k to be real, but the Laplace transform in time gives rise to complex frequencies $\omega = \omega_r + \iota\omega_i$, implying also a complex index of refraction, $N = kc/\omega$.

Now, substituting F_a from Eq. (10) into the Eq. (9) provides the wave equation for the linearized electric field, which admits nontrivial solutions only for

$$\det\left|\frac{\omega^2}{c^2}\epsilon_{ij} + k_i k_j - k^2\delta_{ij}\right| = 0 \tag{11}$$

where the dielectric tensor has the components, $\epsilon_{ij} \equiv \delta_{ij} + (4\pi/\omega)\sigma_{ij}$, explicitly given by

$$\epsilon_{ij} = \delta_{ij} + \sum_a \frac{\omega_{p,a}^2}{\omega^2}\left[\int_{-\infty}^{\infty}d\mathbf{v}\,v_i\frac{\partial F_{a,0}}{\partial v_j} + \int_{-\infty}^{\infty}d\mathbf{v}\,v_i v_j\frac{\mathbf{k}\cdot\partial F_{a,0}/\partial\mathbf{v}}{\omega - \mathbf{k}\cdot\mathbf{v}}\right]. \tag{12}$$

3. Counterstreaming plasmas with intrinsic temperature anisotropies

In order to analyze the unstable plasma modes and their interplay we need a complex anisotropic plasma model including various forms of particle velocity anisotropy. Thus, we consider two counter streaming plasmas (see Fig. 1) with internal temperature anisotropies described by the distribution function (Maxwellian counterstreams)

$$f_0(v_x, v_y, v_z) = v_{th}^{-2}v_{th\perp}^{-1}2\pi^{3/2}\exp\left[-v_x^2 + v_z^2 v_{th}^2\right]\left\{\exp\left[-(v_y + v_0)^2 v_{th,y}^2\right] + \exp\left[-(v_y - v_0)^2 v_{th,y}^2\right]\right\}. \tag{13}$$

Recent investigations have proved that such a model is not only appropriate for a multitude of plasma applications but, in addition, it can be approached analytically very well.

For the sake of simplicity, in what follows we neglect the contribution of ions, which form the neutralizing background, and the electron plasma streams are assumed homogeneous and symmetric (charge and current neutral) with the same densities, $\omega_{p,e,1} = \omega_{p,e,2} = \omega_{p,e}$, equal but opposite streaming velocities, $v_1 = v_2 = v_0$, and the same temperature parameters, i.e., thermal velocities, $v_{th,x,1} = v_{th,z,1} = v_{th,x,2} = v_{th,z,2} = v_{th}$, $v_{th,y,1} = v_{th,y,2} = v_{th,y}$. Furthermore, for each stream, the intrinsic thermal distribution is considered bi-Maxwellian, and the temperature anisotropy is defined by $A_1 = A_2 = A = T_y/T_x = (v_{th,y}/v_{th})^2$. Taking the counterstreaming plasmas symmetric, a condition frequently satisfied with respect to their mass center at rest, provides simple forms for the dispersion relations, and solutions are purely growing exhibiting only a reactive part, $\text{Re}(\omega) = \omega_r \to 0$ and $\text{Im}(\omega) = \Gamma > 0$, and, therefore, a negligible resonant Landau dissipation of wave energy on plasma particles. The anisotropic
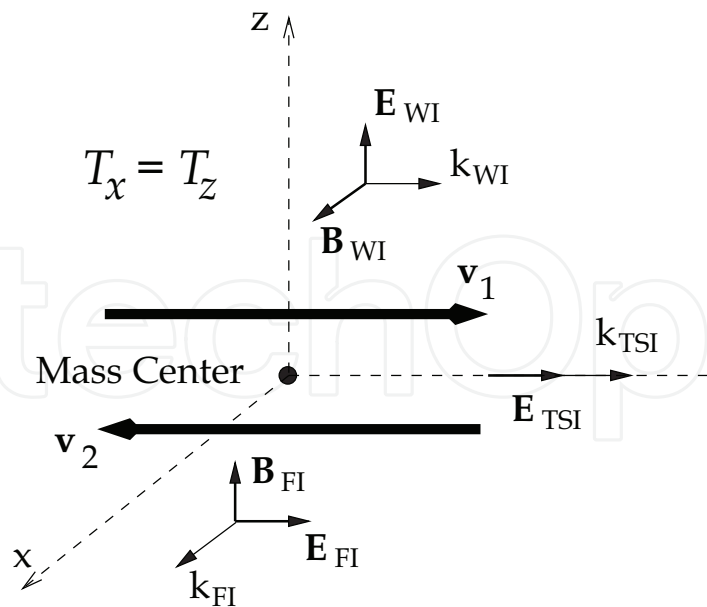
Fig. 1. Sketch of two plasma counter streams moving along y-axis and the instabilities developing in the system: the electromagnetic Weibel instability (WI) driven by an excess of transverse kinetic energy, and the electrostatic two-stream instability (TSI) both propagating along the streams, and the filamentation instability (FI) propagating perpendicular to the streams.
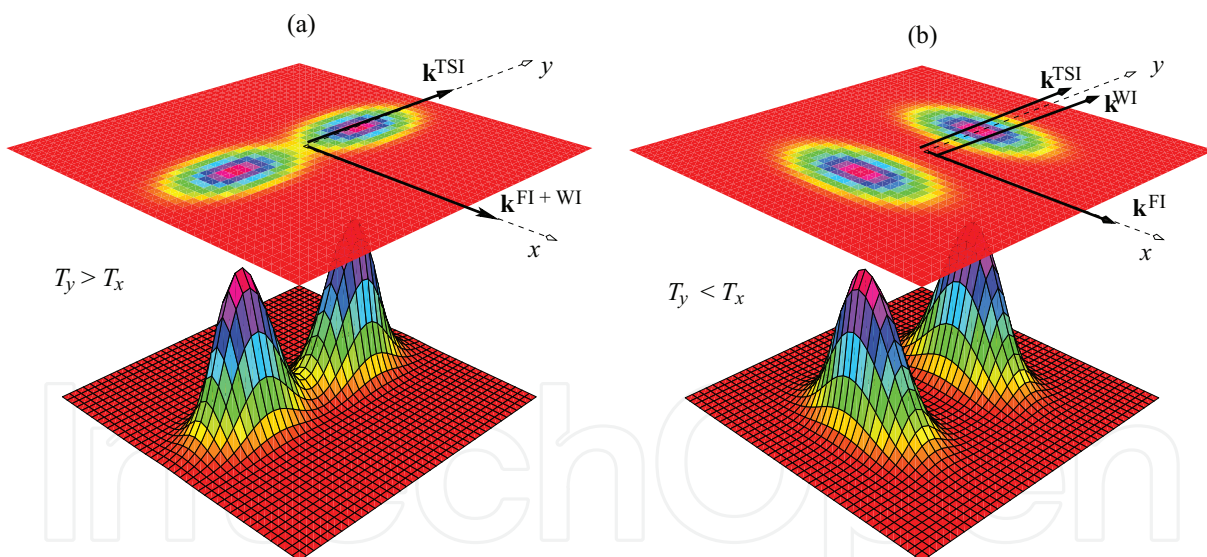

Fig. 2. Sketch of the distribution functions for two symmetric counterstreaming plasmas, and the wave-vectors for the unstable modes expected to develop when (a) $T_x = T_z < T_y$ and (b) $T_x = T_z > T_y$.

counterstreaming distribution functions are illustrated in Fig. 2, for two representative situations: (a) $T_x = T_z < T_y$ and (b) $T_x = T_z > T_y$.

Such a plasma system is unstable against the excitation of the electrostatic two-stream instability as well as the electromagnetic instabilities of the Weibel-type. We limit our analysis to the unstable waves propagating either parallel or perpendicular to the direction of streams. The orientation of these instabilities is given in the Figures 1 and 2.

4. Unstable modes with k ‖ ŷ

First we look for the unstable modes propagating along the streaming direction, $k = k_y$, and due to the symmetry of our distribution function (13), the dispersion relation (11) simplifies to

$$\left(\frac{\omega^2}{c^2}\epsilon_{xx} - k_y^2\right)\left(\frac{\omega^2}{c^2}\epsilon_{zz} - k_y^2\right)\epsilon_{yy} = 0. \tag{14}$$

This equation admits three solutions, viz. two electromagnetic modes

$$\frac{k_y^2 c^2}{\omega^2} = \epsilon_{xx} \qquad \frac{k_y^2 c^2}{\omega^2} = \epsilon_{zz} = 0, \tag{15}$$

and one electrostatic mode

$$\epsilon_{yy} = 0, \tag{16}$$

where the dielectric tensor components are provided by Eq. (12), with our initial unperturbed distribution function given in Eq. (13).

In a finite temperature plasma there is an important departure from the cold plasma model, where no transverse modes could interact with the electrons for wave vectors parallel to the streaming direction, $\mathbf{k} \parallel \hat{\mathbf{y}}$, as no electrons move perpendicularly to the streams. These electrons are introduced here by a non-vanishing transverse temperature of the plasma counter-streams. Furthermore, the electromagnetic modes of Weibel-type and propagating along the streaming direction can be excited only by an excess of transverse kinetic energy, $T_x = T_z > T_y$ (Bret et al.; 2004). These modes are characterized in the next.

4.1 The Weibel instability (k · E = 0, $v_{th} > v_{th,y}$)

Thus, let we consider symmetric counterstreams with an excess of transverse kinetic energy, $T_x = T_z > T_y$, and described by a bi-Maxwellian distribution as given in Eq. (13) and schematically shown Fig. 2 (a). Due to the symmetry of the system (see in Fig. 2 a) the two branches of the transverse modes (Eq. 15) are also symmetric and will be described by the same dispersion relation (Okada et al.; 1977; Bret et al.; 2004; Lazar et al.; 2009c)

$$\frac{k_y^2 c^2}{\omega^2} = \epsilon_{xx}^{WI} = \epsilon_{zz}^{WI} = 1 - \frac{\omega_{p,e}^2}{\omega^2}\left\{1 - \frac{1}{A}\left[1 + \frac{1}{2}\left(f_1 Z(f_1) + f_2 Z(f_2)\right)\right]\right\}, \tag{17}$$

which is written in terms of the well-known plasma dispersion function (Fried & Conte; 1961)

$$Z(f) = \pi^{-1/2}\int_{-\infty}^{\infty}dx\frac{\exp(-x^2)}{x - f}, \quad with \quad f_{1,2} = \frac{\omega \mp k_y v_0}{k_y v_{th,y}}. \tag{18}$$

Numerical solutions of Eq. (17) are displayed in Fig. 3: the growth rates of the Weibel instability are visibly reduced in a counterstreaming plasma and the wave number cutoff is also diminished according to
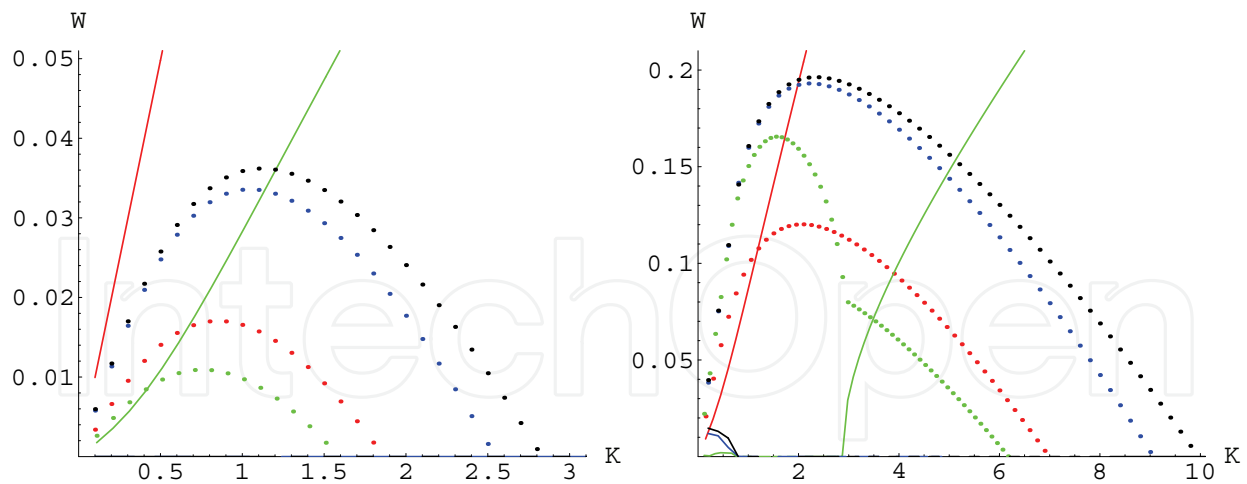
Fig. 3. Numerical solutions of equation (17): with dotted lines are plotted the growth rates, $W = \omega_i/\omega_{pe}$, and with solid lines the real frequency, $W = \omega_r/\omega_{pe}$, for $v_{th,y} = c/30 = 10^7$ m/s, three different streaming velocities, $v_0 = c/10$ (red), $c/30$ (green), $c/100$ (blue), 0 (black), and two anisotropies (a) $v_{th}/v_{th,y} = 3$ and (b) $v_{th}/v_{th,y} = 10$ ($K = kc/\omega_{pe}$, and $c = 3 \times 10^8$ m/s is the speed of light in vacuum).

$$k_{y,c}^{WI} = \frac{\omega_{p,e}}{c}\left\{\frac{1}{A}\left[1 + \frac{v_0}{v_{th,y}}\mathrm{Re}Z\left(\frac{v_0}{v_{th,y}}\right)\right] - 1\right\}^{1/2} < k_{y,c}^{WI}(v_0 = 0). \tag{19}$$

Here, we have taken into account that, for a real argument, the real part of plasma dispersion function is negative: $\mathrm{Re}\,Z(x) = -2\exp(-x^2)\int_0^x dt\exp(t^2) < 0$, and $xZ(x) - xZ(-x) = 2x\mathrm{Re}Z(x)$.

This wave number cutoff must be a real (not complex) solution of Eq. (17) in the limit of $\Gamma(k) = \Im\omega(k) = 0$. For $v_0 = 0$ we simply recover the cutoff wave number of the Weibel instability driven by a temperature anisotropy without streams. According to Eq. (19), in the presence of streams ($v_0 \neq 0$) the threshold of the Weibel instability ($v_{th}^2/v_{th,y}^2 = T/T_y > 1$) grows to

$$\frac{v_{th}^2}{v_{th,y}^2} > 1 + \frac{v_{th}^2 v_0}{v_{th,y}^3}\left|\mathrm{Re}Z\left(\frac{v_0}{v_{th,y}}\right)\right|. \tag{20}$$

We remark in Fig. 3 that the Weibel instability is purely growing ($\omega_r = 0$) not only in a non-streaming plasma ($v_0 = 0$), but in the presence of streams as well. This is, however, valid only for small streaming speeds. Otherwise, for energetic streams with a sufficiently large bulk velocity, larger than the thermal speed along their direction, $v_0 > v_{th,y}$, the instability becomes oscillatory with a finite frequency $\omega_r \neq 0$. As the temperature anisotropy is also large, both these regimes can be identified, the purely growing regime for small wave numbers, and the oscillatory growing regime for large wave numbers (see Fig. 3 b, and Lazar et al. (2009a) for a supplementary analysis).

4.2 Two-stream instability ($k \times E = 0$)

The two-stream instability is an electrostatic unstable mode propagating along the streaming direction and described by the dispersion relation (16), where the dielectric function reads
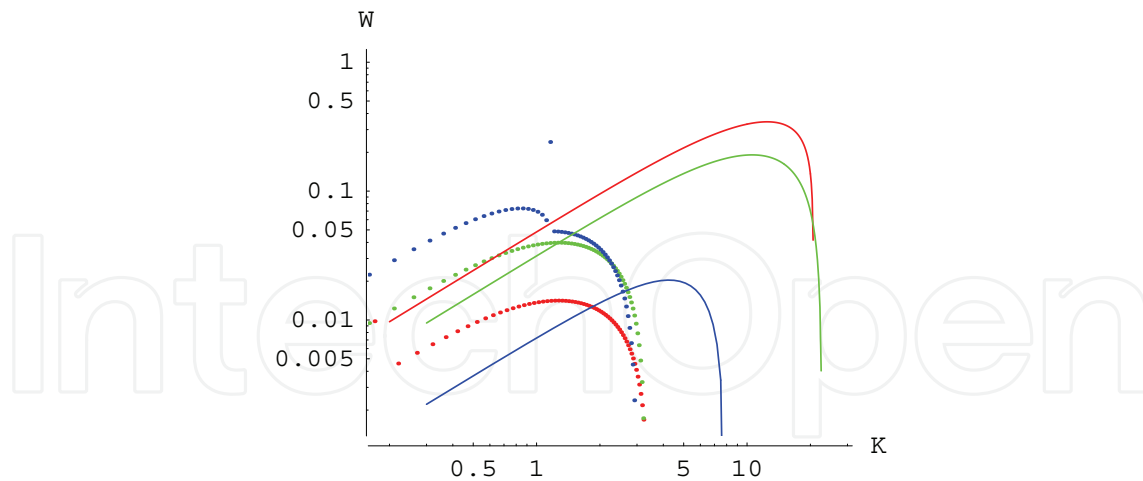
Fig. 4. For a given anisotropy $v_{th}/v_{th,y}$ =5 and streaming speed v_0 = $c/20$, the growth rates (W = ω_i/ω_{pe} versus K = kc/ω_{pe}) of the Weibel instability (dotted lines) increase and those of the two-stream instability (solid lines) decrease with parallel thermal spread of plasma particles: $v_{th,y}$ = $c/100$ (red lines), $c/30$ (green), $c/20$ (blue).

$$\epsilon_{yy}^{\text{TSI}} = 1 + \frac{\omega_{p,e}^2}{k_y^2 v_{th,y}^2}\left[2 + f_1 Z(f_1) + f_2 Z(f_2)\right] = 0. \tag{21}$$

The two-stream instability is inhibited by the thermal spread of plasma particles along the streaming direction. The growth rates can be markedly reduced by increasing $v_{th,y}$. Thus, the two-stream instability has a maximal efficiency in the process of relaxation only for a

$$k_{y,c}^{\text{TSI}} = \frac{\omega_{p,e}}{v_0}\left(1 + \frac{3}{2}\frac{v_{th,y}^2}{v_0^2}\right)^{1/2} \simeq \frac{\omega_{p,e}}{v_0}\left(1 + \frac{3}{4}\frac{v_{th,y}^2}{v_0^2}\right). \tag{22}$$

For a negligible thermal spread, $v_0 \gg v_{th,y}$ (i.e. cold plasmas), the cutoff wave number will depend only on the streaming velocity $k_{y,c}^{\text{TSI}} \to \omega_{p,e}/v_0$.

The instability is purely growing because the streams are symmetric, otherwise it is oscillatory. The growth rates, solutions of Eq. (21), are displayed in Fig. 4 in comparison to the Weibel instability growth rates ($v_{th} > v_{th,y}$), for conditions typically encountered in intergalactic plasma and cosmological structures formation (Lazar et al.; 2009c).

We can extract the first remarks on the interplay of these two instabilities from Fig. 1:

1. When the thermal speed along the streams is small enough, i.e. smaller than the streaming speed, the two-stream instability grows much faster than theWeibel instability (the growth rates of the two-stream instability are much larger than those of the Weibel instability).

2. While the two-stream instability is not affected by the temperature anisotropy, the Weibel instability is strictly dependent on that.

3. While the thermal spread along the streams inhibits the two-stream instability, in the presence of a temperature anisotropy, the same parallel thermal spread enhances the Weibel instability growth rates. In this case, the Weibel instability has chances to arise before the two-stream instability can develop.

Otherwise, the two-stream instability develops first and relaxes the counterstreams to a plateau anisotropic distribution with two characteristic temperatures (bi-Maxwellian). If this thermal anisotropy is large enough, it is susceptible again to relax through aWeibel excitation. How large this thermal anisotropy could be depends not only on the initial bulk velocity of the streams but on their internal temperature anisotropy as well.

Whether it develops as a primary or secondary mechanism of relaxation, the Weibel instability seems therefore to be an important mechanism of relaxation for such counterstreaming plasmas. This has important consequences for experiments and many astrophysical scenarios, providing for example, a plausible explanation for the origin of cosmological magnetic field seeds (Schlickeiser & Shukla; 2003; Lazar et al.; 2009c).

5. Unstable modes with k ⊥ ŷ

There is also another important competitor in this puzzle of kinetic instabilities arising in a counterstreaming plasma, and this is the filamentation instability which is driven by the bulk relative motion of plasma streams and propagates perpendicular to the streams, $\mathbf{k} \perp \hat{\mathbf{y}}$. In this case, we can choose without any restriction of generality, the propagation direction along x-axis, $k = k_x$, and in this case the dispersion relation (11) becomes

$$\epsilon_{xx}\left(\frac{\omega^2}{c^2}\epsilon_{yy} - k_x^2\right)\left(\frac{\omega^2}{c^2}\epsilon_{zz} - k_x^2\right) = 0. \tag{23}$$

This equation admits three branches of solutions, one electrostatic and two symmetric electromagnetic modes, but only the electromagnetic mode is unstable and this is the filamentation instability.

5.1 Filamentation instability ($E = E_y, k = k_x$)

The filamentation instability does not exist in a nonstreaming plasma and has originally been described by Fried (1959). The mechanism of generation is similar to that of the Weibel in stability: any small magnetic perturbation is amplified by the relative motion of two counter-streaming plasmas without any contribution of their intrinsic temperature anisotropy. This instability is also purely growing and has the electric field oriented along the streaming direction. Therefore, for a simple characterization of the filamentation instability, first we assume the streams thermally isotropic, $A \equiv T_y/T_x = 1$, with isotropic velocity distributions of Maxwellian type. The dispersion relation (23) provides then for the electromagnetic modes

$$\frac{k_x^2 c^2}{\omega^2} = \epsilon_{yy}^{\mathrm{FI}} = 1 + \frac{\omega_{p,e}^2}{\omega^2}\left[2\frac{v_0^2}{v_{th}^2} + \left(1 + 2\frac{v_0^2}{v_{th}^2}\right)\frac{\omega}{k_x v_{th}}Z\left(\frac{\omega}{k_x v_{th}}\right)\right]. \tag{24}$$

The unstable purely growing solutions describe the filamentation instability, and the growth rates are numerically derived and displayed with solid lines in Fig. 5. We should observe that they are restricted to wave-numbers less than a cutoff given by

$$k_{x,c}^{\mathrm{FI}} = \sqrt{2}\frac{\omega_{pe}}{c}\frac{v_0}{v_{th}}. \tag{25}$$
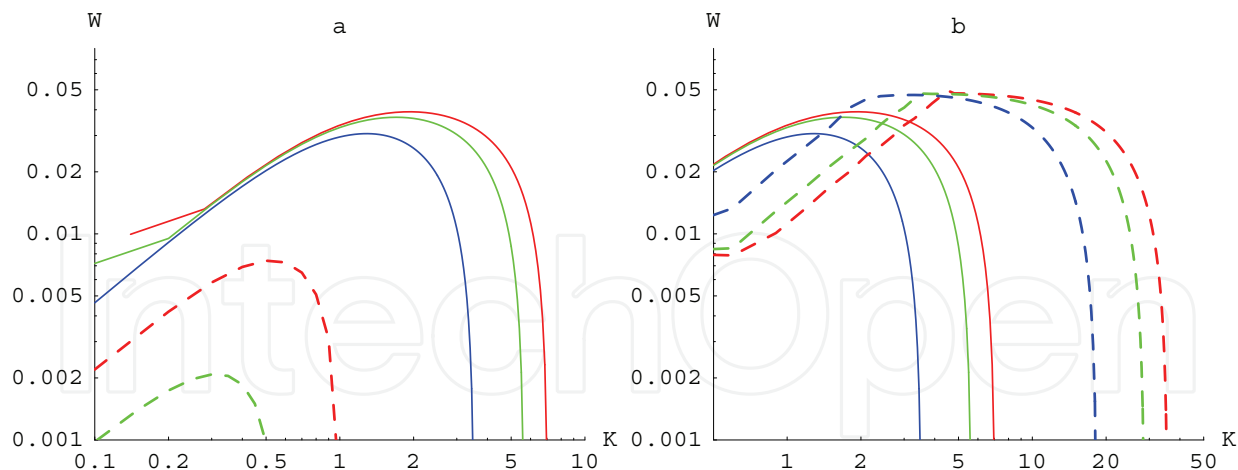
Fig. 5. The growth rates of the filamentation instability (solid lines) as given by Eq. (24) for a streaming speed $v_0 = c/20$, and different parallel thermal spread of plasma particles: $v_{th,y} = c/100$ (red lines), $c/80$ (green), $c/50$ (blue). The growth rates of the cumulative filamentation-Weibel instability given by (26) are shown with dashed lines for (a) $v_{th}/v_{th,y} = 5$ and (b) $v_{th}/v_{th,y} = 1/5$. The coordinates are scaled as $W = \omega_i/\omega_{pe}$ versus $K = kc/\omega_{pe}$.

5.2 Cumulative filamentation-Weibel instability ($E = E_y$, $k = k_x$, $A \neq 0$).

Since plasma streams exhibit an internal temperature anisotropy (see Fig. 2, a and b) the filamentation instability can be either enhanced by the cumulative effect of the Weibel instability when $T_y > T_x$ (see Fig. 5, b), or in the opposite case of $T_y < T_x$, the effective velocity anisotropy of plasma particle decreases and the instability is suppressed (see Fig. 5, a).

For streams with a finite intrinsic temperature anisotropy, $A \neq 0$, the dispersion relation (23) provides for the electromagnetic modes

$$\frac{k_x^2 c^2}{\omega^2} = \epsilon_{yy}^{\text{FWI}} = 1 - \frac{\omega_{p,e}^2}{\omega^2} \left\{ 1 - \left(A + 2\frac{v_0^2}{v_{th}^2} \right) \left[1 + \frac{\omega}{k_x v_{th}} Z\left(\frac{\omega}{k_x v_{th}} \right) \right] \right\}. \tag{26}$$

In this case the unstable purely growing solutions describe the cumulative filamentation-Weibel instability, and the growth rates are displayed with dashed lines in Fig. 5. Again, we remark that the unstable solutions are restricted to wave-numbers less than a cutoff value which is given by

$$k_{x,c}^{\text{FWI}} = \frac{\omega_{pe}}{c} \left(A - 1 + 2\frac{v_0^2}{v_{th}^2} \right)^{1/2}. \tag{27}$$

The condition of existence for Eq. (27) provides the threshold of the cumulative filamentation-Weibel instability:

$$v_{th} < \left(v_{th,y}^2 + 2v_0^2 \right)^{1/2} \equiv v_{th,c}. \tag{28}$$

For interested readers, supplementary analysis of this instability can be found in the recent papers of Bret et al. (2004, 2005a,b); Bret & Deutsch (2006); Lazar et al. (2006); Stockem & Lazar (2008); Lazar (2008); Lazar et al. (2008, 2009d, 2010). Here we continue to consider

symmetric counterstreams making a simple description of this instability and compare to the other unstable modes discussed above.

5.2.1 $A = T_y/T_x < 1$

As plasma streams are transversally hotter, the effective anisotropy of the particle velocity distribution with respect to their mass center at rest decreases, and the growth rates of the cumulative filamentation-Weibel instability become also smaller (see Fig. 5 a). This instability is inhibited by a surplus of transverse kinetic energy (Lazar et al.; 2006; Stockem & Lazar; 2008). Furthermore, it has two competitors in the process of relaxation: the two-stream instability and theWeibel instability, both propagating parallel to the streams and described in the sections above.

For a complete characterization of their interplay, the growth rates of these three instabilities are displayed in Fig. 6 for the same conditions used in Fig. 4 but, for clarity, only two cases are plotted: $v_{th,y} = c/100$ (red lines), $c/30$ (green). Thus, the filamentation (cumulative filamentation-Weibel) growth rates (plotted with dashed lines) are smaller than the Weibel instability growth rates (dotted line), which are, in turn, smaller than those of the filamentation instability (solid lines). Moreover, when thermal spread of plasma particles is large enough, the surplus of kinetic energy transverse to the streams compensates the opposite particle velocity anisotropy due to bulk (counterstreaming) motion along the streams, and the effective anisotropy of plasma particles vanishes. In this case, the filamentation instability is completely suppressed: no growth rates are found in Fig. 6 for $v_{th,y} = c/30$ (no green dashed line). That is confirmed by the threshold condition (28): the instability exists only for $v_{th} < v_{th,c} \equiv \left(v_{th,y}^2 + 2v_0^2 \right)^{1/2} \simeq c/14$, and in Fig. 6 this condition is satisfied only in the case of $v_{th} = A^{-1/2} v_{th,y} = \sqrt{5}c/100 < c/14$ (red dashed line), but not for $v_{th} = A^{-1/2} v_{th,y} = \sqrt{5}c/30 > c/14$ (no green dashed line).
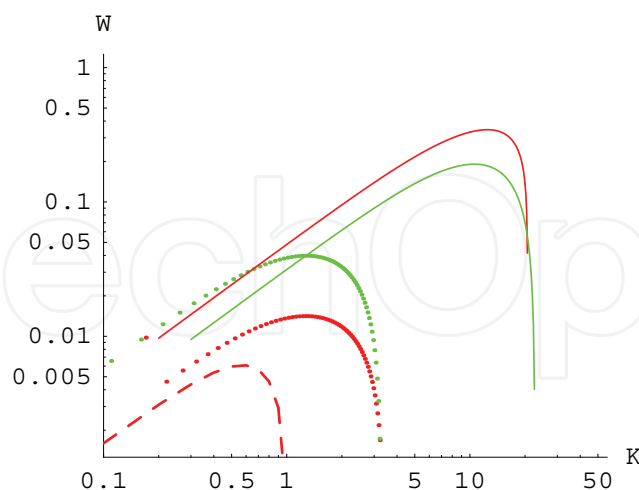

Fig. 6. The growth rates (W = ω_i/ω_{pe} versus K = kc/ω_{pe}) of the Weibel instability (dotted lines), the two-stream instability (solid lines), and the filamentation (cumulative filamentation-Weibel) instability (dashed line) for the same plasma parameters considered in Fig. 4: $v_0 = c/20$, $v_{th,y} = c/100$ (red lines), $c/30$ (green). The excess of transverse kinetic energy , $v_{th}/v_{th,y} = 5$, diminishes the growth rates of the filamentation instability (red dashed line), or even suppresses the instability (no green dashed line).

In section **4.2.** we have shown that the thermal spread of plasma particles along the streams prevents a fast developing of the two-stream instability, which, in general, is the fastest mechanism of relaxation. Furthermore, here it is proved that kinetic effects arising from the perpendicular temperature of the streams could stabilize the non-resonant filamentation mode. These results have a particular importance for the beam-plasma experiments, specifically, in the fast ignition scenario for inertial confinement fusion, where these instabilities must be avoided.

5.2.2 $A = T_y/T_x > 1$

In the opposite case, when plasma streams exhibit an excess of parallel kinetic energy, $A = T_y/T_x > 1$, theWeibel effect due to the temperature anisotropy cumulates to the filamentation instability given by the relative motion of counterstreaming plasmas, and yields an enhancing of the growth rate (see Fig. 5 b).

In this case, there is only one competitor for the cumulative filamentation-Weibel instability, and this is the two-stream electrostatic instability. The growth rates of these two instabilities are plotted in Figures 7 and 8 for several representative situations.

In Fig. 7 we consider a situation similar to that from Fig. 4 but this time with an excess of parallel kinetic energy. Thus, for a given anisotropy, $v_{th,y}/v_{th} = 5$, the growth rates of the two-stream instability (solid lines), are inhibited by the parallel thermal spread of plasma particles and decrease. The growth rates of the filamentation instability (dashed lines) are relatively constant, but the instability is constrained to smaller wave-numbers according to Eq. (27).

On the other hand, in Fig. 8 we change and follow the variation of the growth rates with the anisotropy: the streaming velocity is higher but still not relativistic, $v_0 = c/10$, $v_{th} = c/100$, and the anisotropy takes three values, $v_{th,y}/v_{th} = 1$ (red lines), 4 (green), and 10 (blue). In this case the cumulative filamentation-Weibel instability becomes markedly competitive, either extending to larger wave-numbers according to Eq. (27), or reaching at saturation, maximums growth rates comparable or even much larger than those of the two-stream
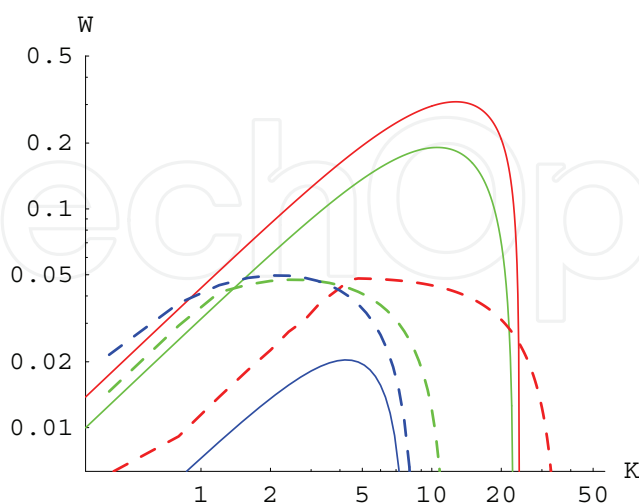

Fig. 7. The growth rates (W = ω_i/ω_{pe} versus K = kc/ω_{pe}) of the two-stream instability (solid lines), and the filamentation instability (dashed lines) for the same plasma parameters considered in Fig. 4: $v_0 = c/20$, $v_{th,y} = c/100$ (red lines), $c/30$ (green), $c/20$ (blue), but an opposite temperature anisotropy, $v_{th}/v_{th,y} = 1/5$.
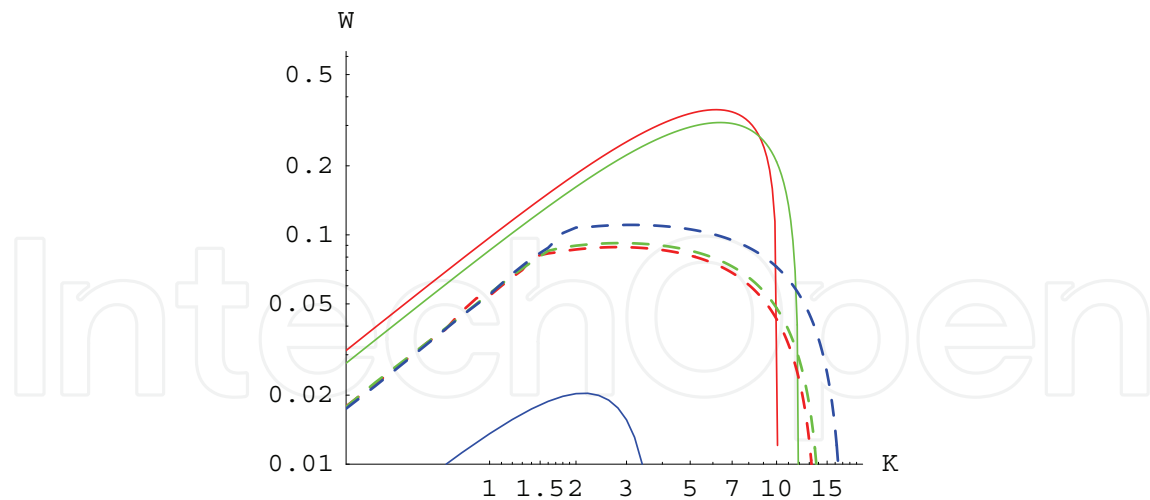
Fig. 8. The same as in Fig. 7 but for: $v_0 = c/10$, $v_{th} = c/100$ and the anisotropy $v_{th,y}/v_{th} = 1$ (red lines), 4 (green), 10 (blue).

instability. The main reason for that is clear, the two-stream instability is inhibited by increasing T_y, and in this case, the cumulative filamentation-Weibel instability can provide the fastest mechanism of relaxation for such counterstreaming plasmas.

This instability can explain the origin of the magnetic field fluctuations frequently observed in the solar wind, and which are expected to enhance along the temperature anisotropy thresholds.

6. Discussion and summary

In this chapter, we have described the interplay of kinetic plasma instabilities in a counterstreaming plasma including a finite and anisotropic thermal spread of charge carriers. Such a complex and anisotropic plasma model is maybe complicated but it allows for a realistic investigation of a wide spectra of plasma waves and instabilities. Small plasma perturbations, whether they are electrostatic or electromagnetic, can develop and release the free energy residing in the bulk relative motion of streams or in thermal anisotropy. Two types of growing modes have been identified as possible mechanisms of relaxation: an electrostatic growing mode, which is the two-stream instability, and two electromagnetic growing modes, which are the Weibel instability and the filamentation instability, respectively. The last two can cumulate leading either to enhancing or quenching the electromagnetic instability.

The most efficient wave mode capable to release the excess of free energy and relax the counterstreaming distribution, will be the fastest growing wave mode, and this is the mode with the largest maximum growth rate. Thus, first we have presented the dispersion approach and the dispersion relations of the unstable modes, and then we have calculated numerically their growth rates for various plasma parameters. Possible applications in plasma astrophysics and fusion experiments have also been reviewed for each case in part.

When the intrinsic temperature anisotropy is small, the two stream electrostatic instability develops first and relaxes the counterstreams to an anisotropic bi-Maxwellian plasma, which is unstable against the excitation of Weibel instability.

If the intrinsic temperature anisotropy increases, the electromagnetic instabilities can be faster than the two-stream instability. This could be the case of a plasma hotter along the

streaming direction, when the two-stream instability is inhibited, but the contributions of the filamentation and Weibel instabilities cumulate enhancing the magnetic instability. Otherwise, if the plasma kinetic energy transverse to the streams exceeds the parallel kinetic energy, the anisotropy in velocity space decreases and becomes less effective, and the filamentation instability is reduced or even suppressed. However, in this case a Weibel-like instability arises along the streaming direction, and if the temperature anisotropy is large enough, this instability becomes the fastest mechanism of relaxation with growth rates larger than those of the two-stream and filamentation instabilities.

We have neglected any influence of the ambient stationary fields, but the results presented here are also appropriate for the weakly magnetized (high-beta) plasmas widely present in astrophysical scenarios.

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Wave Propagation in Materials for Modern Applications

Edited by Andrey Petrin

In the recent decades, there has been a growing interest in micro- and nanotechnology. The advances in nanotechnology give rise to new applications and new types of materials with unique electromagnetic and mechanical properties. This book is devoted to the modern methods in electrodynamics and acoustics, which have been developed to describe wave propagation in these modern materials and nanodevices. The book consists of original works of leading scientists in the field of wave propagation who produced new theoretical and experimental methods in the research field and obtained new and important results. The first part of the book consists of chapters with general mathematical methods and approaches to the problem of wave propagation. A special attention is attracted to the advanced numerical methods fruitfully applied in the field of wave propagation. The second part of the book is devoted to the problems of wave propagation in newly developed metamaterials, micro- and nanostructures and porous media. In this part the interested reader will find important and fundamental results on electromagnetic wave propagation in media with negative refraction index and electromagnetic imaging in devices based on the materials. The third part of the book is devoted to the problems of wave propagation in elastic and piezoelectric media. In the fourth part, the works on the problems of wave propagation in plasma are collected. The fifth, sixth and seventh parts are devoted to the problems of wave propagation in media with chemical reactions, in nonlinear and disperse media, respectively. And finally, in the eighth part of the book some experimental methods in wave propagations are considered. It is necessary to emphasize that this book is not a textbook. It is important that the results combined in it are taken "from the desks of researchers". Therefore, I am sure that in this book the interested and actively working readers (scientists, engineers and students) will find many interesting results and new ideas.

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