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Zonal flow excitation in plasmas by electron-temperature-gradient modes

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Abstract. The nonlinear coupling between short-wavelength electron-temperature-gradient (ETG) modes and zonal flows in plasmas is considered. The mode-coupling equations are derived by using a Boltzmann ion distribution and a fluid electron response described by the hydrodynamic and energy equations. A dispersion relation for the nonlinearly coupled ETG modes and the zonal flows is derived. The results show enhanced zonal flows, which can affect the electron energy transport in tokamaks and stellarators.

1. Introduction

Turbulence driven by micro-instabilities is thought to be responsible for the cross-field electron heat transport which is generally larger than the collision-driven fluxes. It is a widely held view that short-wavelength (in comparison with the ion thermal gyroradius $\rho_{\rm i}$) toroidal electron-temperature-gradient (ETG) modes [1–10] can cause anomalously high levels of electron energy losses. The ETG modes involve unmagnetized hot ions with a Boltzmann density perturbation $n_{\rm i} = n_0(r)\exp(-Z_{\rm i}e\phi/T_{\rm i})$, while the magnetized electrons have $c\mathbf{E}\times\mathbf{B}_0/B_0^2$, diamagnetic, and polarization drifts. Here n_0 is the unperturbed plasma number density, $Z_{\rm i}e$ is the ion charge, e is the magnitude of the electron charge, ϕ is the fluctuating electrostatic potential, $T_{\rm i}$ is the ion temperature, c is the speed of light in vacuum, $\mathbf{E} = -\nabla\phi$ is the electrostatic field, and $\mathbf{B}_0(r)$ is the inhomogeneous magnetic field. Since, in an inhomogeneous magnetic field, the divergence of the electron diamagnetic drift is non-zero, there is a finite electron temperature perturbation, besides the electron density perturbation. In the presence of an electron temperature gradient, the temperature and density perturbations are out of phase, and drive the ETG modes at non-thermal levels. This leads to anomalous cross-field electron thermal transport. The ETG modes cause no particle and ion energy transport in view of the Boltzmann ion distribution. There are experimental cases [11, 12] in which a distinctly anomalous electron thermal transport is observed without accompanying anomalous ion thermal transport or ion-scale fluctuations. Recent computer simulations [13, 14] have predicted the excitation of zonal (sheared) flows

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in electron temperature gradient driven turbulence. Zonal flows seem to control [14] the electron energy transport in non-uniform plasmas. Moreover, Jenko and Dorland [15] have carried out simulation studies of the nonlinear development of purely curvature-driven ETG mode turbulence and large-amplitude streamers.

In this paper, we present an analytical study of the nonlinear coupling between short-wavelength ETG modes and long-wavelength zonal flows in a non-uniform plasma with electron pressure and magnetic field inhomogeneities. A set of nonlinear mode-coupling equations is derived by using a hybrid approach in which the ions participating in the toroidal ETG mode dynamics obey a Boltzmann distribution, while the fluid electrons are magnetized. On the other hand, the zonal flows are driven by the stresses of the ETG modes. Our mode coupling equations are Fourier decomposed to obtain a dispersion relation which shows how the ETG pump and its sidebands interact to enhance the zonal flows due to modulational interactions. The present theoretical work thus lends support to the simulation results that have been reported in [14].

2. Governing equations

Let us consider nonlinear interactions between large-amplitude electrostatic ETG modes and azimuthally symmetric zonal flows in a non-uniform electron–ion plasma containing an inhomogeneous magnetic field $\mathbf{B}_0(r)$ and an electron pressure gradient $\partial p_{e0}/\partial r$, where p_{e0} is the unperturbed pressure. At equilibrium, $p_{e0} + B_0^2/8\pi$ is consequently a constant. Since the perpendicular wavelength of the ETG modes here is shorter than the ion gyroradius, the unmagnetized ions follow a straight-line orbit across $\mathbf{B}_0 = \hat{\mathbf{e}}_\parallel B_0(r)$. The corresponding ion density perturbation is

$$n_{i1} = -n_0(r)\frac{Z_i e\phi}{T_i}, \tag{1}$$

where $\hat{\mathbf{e}}_\parallel = \mathbf{B}_0(r)/|\mathbf{B}_0|$. The electron density perturbation in the electrostatic field of the ETG mode is obtained from the continuity equation

$$\frac{\partial n_{e1}}{\partial t} + \nabla\cdot\left[n_0(r)\mathbf{v}_{e\perp} + n_{e1}\frac{c}{B_0}\hat{\mathbf{e}}_\parallel\times\nabla\psi + n_{z1}\frac{c}{B_0}\hat{\mathbf{e}}_\parallel\times\nabla\phi\right] = 0, \tag{2}$$

where n_{e1} (n_{z1}) is the electron number density perturbation associated with the ETG (zonal flow) mode, and ψ is the potential of the zonal flow. In (2), the perpendicular electron velocity in the zonal flow field is to leading order $(c/B_0)\hat{\mathbf{e}}_\parallel\times\nabla\psi$, since the zonal flows are set up on a time scale much larger than the ion gyroperiod.

The perpendicular (to $\hat{\mathbf{e}}_\parallel$) component of the electron fluid velocity $\mathbf{v}_{e\perp}$ is for $|\partial/\partial t| \ll \omega_{ce}$ and $\rho_e^2|\nabla_\perp^2| \ll 1$

$$\mathbf{v}_{e\perp} \approx \mathbf{v}_E + \mathbf{v}_{De} + \mathbf{v}_{\pi e} + \frac{c}{B_0\omega_{ce}}\left(\frac{\partial}{\partial t} + \mathbf{v}_{e\perp}\cdot\nabla\right)\nabla_\perp\phi$$

$$+ \frac{c^2}{B_0^2\omega_{ce}}[(\hat{\mathbf{z}}\times\nabla\phi\cdot\nabla)\nabla_\perp\psi + (\hat{\mathbf{z}}\times\nabla\psi\cdot\nabla)\nabla_\perp\phi], \tag{3}$$

where $\omega_{ce} = eB_0/m_e c$ is the electron gyrofrequency, m_e is the electron mass, ρ_e is the thermal electron gyroradius, $\mathbf{v}_E = (c/B_0)\hat{\mathbf{e}}_\parallel\times\nabla\phi$, $\mathbf{v}_{De} = -(c/eB_0 n_e)\hat{\mathbf{e}}_\parallel\times\nabla p_e$ is the electron diamagnetic drift velocity, $p_e = n_e T_e$ is the electron pressure, T_e is the electron temperature, and $\mathbf{v}_{\pi e} = -(\hat{\mathbf{e}}_\parallel\times\nabla\cdot\mathbf{\Pi}_e)/en_e B_0$ is the drift velocity due to the collisionless gyroviscosity tensor $\mathbf{\Pi}_e$ [16].

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Inserting (3) into (2) and using the electron fluid velocity and density perturbation associated with the zonal flow, namely,

$$\mathbf{u}_{e\perp} \approx \frac{c}{B_0}\hat{\mathbf{e}}_\parallel \times \nabla\psi + \frac{c}{B_0\omega_{ce}}\frac{\partial}{\partial t}\nabla_\perp\psi \tag{4}$$

and

$$n_{z1} = -\frac{cn_0}{B_0\omega_{ce}}\nabla_\perp^2\psi, \tag{5}$$

we obtain

$$\left(\frac{\partial}{\partial t} + \mathbf{V}_B\cdot\nabla + \frac{c}{B_0}\hat{\mathbf{e}}_\parallel\times\nabla\psi\cdot\nabla\right)n_{e1} + \frac{n_0}{T_{e0}}\mathbf{V}_B\cdot\nabla T_{e1} - c\hat{\mathbf{e}}_\parallel\times\nabla\left(\frac{n_0}{B_0}\right)\cdot\nabla\phi$$

$$+ \frac{cn_0}{B_0\omega_{ce}}\frac{\partial}{\partial t}\nabla_\perp^2\phi + \frac{c^2n_0}{B_0^2\omega_{ce}}(\hat{\mathbf{e}}_\parallel\times\nabla\psi\cdot\nabla)\nabla_\perp^2\phi = 0, \tag{6}$$

where $\mathbf{V}_B = (cT_{e0}/eB_0)\hat{\mathbf{e}}_\parallel\times[\nabla\ln B_0 + (\hat{\mathbf{e}}_\parallel\cdot\nabla)\hat{\mathbf{e}}_\parallel] \simeq 2cT_{e0}/eB_0R$ is the electron magnetic drift velocity including the ∇B_0 and the curvature effects, T_{e0} (T_{e1}) is the equilibrium (fluctuating part of the) electron temperature, and R represents the radius of the magnetic field curvature. The zonal flow electron density perturbation n_{z1} is obtained by inserting (4) into the electron continuity equation. It then turns out that the electron polarization drift produces an insignificant electron density perturbation associated with the zonal flows.

The electron energy equation [6] determining the electron temperature perturbation T_{e1} is for our purposes [7]

$$\left(\frac{\partial}{\partial t} + \frac{5}{3}\mathbf{V}_B\cdot\nabla\right)T_{e1} - \frac{2}{3}\frac{T_{e0}}{n_0}\frac{\partial n_{e1}}{\partial t} + e\left(\frac{2}{3}\mathbf{V}_N - \mathbf{V}_T\right)\cdot\nabla\phi$$

$$= -\frac{c}{B_0}\hat{\mathbf{e}}_\parallel\times\nabla\psi\cdot\nabla T_{e1} + \frac{2cT_{e0}}{3n_0B_0}\hat{\mathbf{e}}_\parallel\times\nabla\psi\cdot\nabla n_{e1} - \frac{2c^2T_{e0}}{3B_0^2\omega_{ce}}\hat{\mathbf{e}}_\parallel\times\nabla\phi\cdot\nabla\nabla_\perp^2\psi, \tag{7}$$

where $\mathbf{V}_N = (cT_{e0}/eB_0)\hat{\mathbf{e}}_\parallel\times\nabla\ln n_0(r)$ and $\mathbf{V}_T = (cT_{e0}/eB_0)\hat{\mathbf{e}}_\parallel\times\nabla\ln T_{e0}(r)$. In (7) we have ignored the electron heat conduction and the electron energy relaxation. This is justified as long as the ETG mode frequency is much larger than $\nu_e\rho_e^2\nabla^2$ and $m_e\nu_e/m_i$, where ν_e is the electron–ion collision frequency, ρ_e is the electron gyroradius, and m_e/m_i is the electron-to-ion mass ratio.

By using (1) we can now eliminate n_{e1} from (6) and (7), invoking the quasi-neutral approximation $n_{e1} \approx Z_in_{i1}$, which holds for long-wavelength (in comparison with the ion Debye radius) ETG modes, obtaining

$$\left(1-\rho_a^2\nabla_\perp^2\right)\frac{\partial\phi}{\partial t} + (\mathbf{V}_B+\mathbf{V}_{nB})\cdot\nabla\phi - \frac{\tau}{Z_ie}\mathbf{V}_B\cdot\nabla T_{e1} = -\frac{c}{B_0}\hat{\mathbf{e}}_\parallel\times\nabla\psi\cdot\nabla\left(\phi-\rho_a^2\nabla_\perp^2\phi\right) \tag{8}$$

and

$$\left(\frac{\partial}{\partial t} + \frac{5}{3}\mathbf{V}_B\cdot\nabla\right)T_{e1} + \frac{2Z_ie}{3\tau}\frac{\partial\phi}{\partial t} + e\left(\frac{2}{3}\mathbf{V}_N - \mathbf{V}_T\right)\cdot\nabla\phi$$

$$= -\frac{c}{B_0}\hat{\mathbf{e}}_\parallel\times\nabla\psi\cdot\nabla T_{e1} - \frac{2Z_iec}{3B_0\tau}\hat{\mathbf{e}}_\parallel\times\nabla\psi\cdot\nabla\phi, \tag{9}$$

where $\rho_a = c_a/\omega_{ce}\sqrt{Z_i}$ is the electron thermal gyroradius at the ion temperature, $c_a = (T_i/m_e)^{1/2}$ is the electron acoustic speed, and $\tau = T_i/T_{e0}$. Furthermore, we

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have introduced the symbol $\mathbf{V}_{nB} = (cT_{\rm i}/Z_{\rm i}en_0)\hat{\mathbf{e}}_\parallel \times \nabla[n_0(r)/B_0(r)]$, and assumed that $|\partial/\partial t| \gg \mathbf{v}_{\rm De}\cdot\nabla$.

The equation for the azimuthally symmetric zonal flows is obtained from the modified charge density conservation equation

$$\frac{\partial}{\partial t}\nabla_\perp^2\psi + 4\pi e\nabla\cdot[n_0(\mathbf{u}_{\rm e\perp} - \mathbf{u}_{\rm i\perp})] = 0, \tag{10}$$

where the perpendicular component of the ion fluid velocity involved in the zonal flow dynamics is

$$\mathbf{u}_{\rm i\perp} \approx \frac{c}{B_0}\hat{\mathbf{e}}_\parallel \times \nabla\psi - \frac{c}{B_0\omega_{\rm ci}}\left[\left(\frac{\partial}{\partial t} - \mu_{\rm i}\nabla_\perp^2\right)\nabla_\perp\psi + \frac{c}{B_0}\langle(\hat{\mathbf{e}}_\parallel \times \nabla\phi\cdot\nabla)\nabla_\perp\phi\rangle\right]$$
$$+ \frac{c^2}{B_0^2\omega_{\rm ci}}\hat{\mathbf{e}}_\parallel \times \nabla|\nabla_\perp\phi|^2, \tag{11}$$

yielding for $\omega_{\rm pi} \gg \omega_{\rm ci}$

$$\left(\frac{\partial}{\partial t} - \mu_{\rm i}\nabla_\perp^2\right)\nabla_\perp^2\psi = -\frac{c}{B_0}\langle(\hat{\mathbf{e}}_\parallel \times \nabla\phi\cdot\nabla)\nabla_\perp^2\phi\rangle, \tag{12}$$

where $\omega_{\rm pi}$ is the ion plasma frequency, $\mu_{\rm i} = 0.3\nu_{\rm i}\rho_{\rm i}^2$ is the ion gyroviscosity [16], $\nu_{\rm i}$ is the ion collision frequency, and the angular bracket denotes averaging over one period $(2\pi/\omega_0)$ of the ETG modes which have the frequency ω_0. Equation (11) includes the linear ion polarization drift [16], damping of zonal flows due to the ion gyroviscosity, as well as the advection nonlinearity involving the ion velocity in the ETG mode. In fact, the last two terms on the right-hand side of (12) come from the averaging of the advection term $\mathbf{v}_{\rm i\perp}\cdot\nabla\mathbf{v}_{\rm i\perp}$, where $\mathbf{v}_{\rm i\perp} \approx (c/B_0)\hat{\mathbf{e}}_\parallel \times \nabla\phi - i(c\omega_0/B_0\omega_{\rm ce})(1 + \omega_{\rm ce}^2/\omega_{\rm pe}^2)\nabla_\perp\phi$, and $\omega_{\rm pe}$ is the electron plasma frequency.

Equations (8), (9), and (12) are our desired equations for studying the generation of azimuthally symmetric zonal flows by large-amplitude ETG modes in a non-uniform plasma containing electron pressure and magnetic field inhomogeneities.

3. Nonlinear dispersion relation

The nonlinear interactions between a finite-amplitude ETG pump wave $(\omega_0, \mathbf{k}_0)$ and zonal flows $(\omega, \mathbf{k})$ excite upper and lower ETG sidebands $(\omega_\pm, \mathbf{k}_\pm)$. Thus, we decompose the ETG wave potential and electron temperature perturbation as

$$\phi = \phi_{10+}\exp(-i\omega_0 t + i\mathbf{k}_0\cdot\mathbf{r}) + \phi_{10-}\exp(i\omega_0 t - i\mathbf{k}_0\cdot\mathbf{r})$$
$$+ \sum_{+,-}\phi_\pm\exp(-i\omega_\pm t + i\mathbf{k}_\pm\cdot\mathbf{r}) \tag{13}$$

and

$$T_{\rm e1} = T_{10+}\exp(-i\omega_0 t + i\mathbf{k}_0\cdot\mathbf{r}) + T_{10-}\exp(i\omega_0 t - i\mathbf{k}_0\cdot\mathbf{r})$$
$$+ \sum_{+,-}T_\pm\exp(-i\omega_\pm t + i\mathbf{k}_\pm\cdot\mathbf{r}), \tag{14}$$

where $\omega_\pm = \omega \pm \omega_0$ and $\mathbf{k}_\pm = \mathbf{k} \pm \mathbf{k}_0$ are the frequencies and wave vectors of the ETG sidebands, and the subscript $10\pm$ $(\pm)$ stands for the ETG pump (sidebands).

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Inserting (13) and (14) into (8) and (9), letting $\psi = \hat{\psi}\exp(-i\omega t + \mathbf{k}\cdot\mathbf{r})$, Fourier analysing and matching the phasors, and assuming that the wavelength of the ETG mode is much smaller than the scale sizes of the equilibrium density, equilibrium electron temperature, and magnetic field inhomogeneities, we obtain after some straightforward algebra

$$D_{\pm}\phi_{\pm} \approx \pm i\frac{c}{B_0}\hat{\mathbf{e}}_{\parallel}\times\mathbf{k}\cdot\mathbf{k}_0\hat{\psi}\phi_{10\pm}, \tag{15}$$

where

$$\begin{aligned} D_{\pm} = {} & \left\{\left(1+k_{\perp\pm}^2\rho_{\mathrm{a}}^2\right)\omega_{\pm}^2 - \omega_{\pm}\left[(10/3)\omega_{B\pm}+\omega_{nB\pm}+5\omega_{B\pm}k_{\perp\pm}^2\rho_{\mathrm{a}}^2/3\right]+\Omega_{\pm}^2\right\} \\ & \times\left\{\left(1+k_{\perp 0}^2\rho_{\mathrm{a}}^2\right)(\omega_{\pm}-5\omega_{B\pm}/3)-(2\omega_{B\pm}/3)\right. \\ & \left.\times\left[1-(\tau\omega_{N0}-1.5\tau\omega_{T0}+\omega_0)/(\omega_0-5\omega_{B0}/3)\right]\right\}^{-1}, \end{aligned}$$

with $\omega_{B\pm} = \mathbf{k}_{\pm}\cdot\mathbf{V}_B, \omega_{nB\pm} = \mathbf{k}_{\pm}\cdot\mathbf{V}_{nB}, \omega_{T\pm} = \mathbf{k}_{\pm}\cdot\mathbf{V}_T$, $\omega_{N\pm} = \mathbf{k}_{\pm}\cdot\mathbf{V}_N$, and $\Omega_{\pm}^2 = (5/3)\omega_{B\pm}(\omega_{B\pm}+\omega_{nB\pm}) - (2\tau/3)\omega_{B\pm}(\omega_{N\pm}-1.5\omega_{T\pm})$. Replacing $\mathbf{k}_{\pm}$ by $\mathbf{k}_0$ in the latter definitions we obtain the values for ω_{B0}, ω_{T0}, and ω_{N0}. Furthermore, inserting (13) and (14) into (12) and Fourier analysing, we have

$$(\omega + i\Gamma_{\mathrm{z}})\hat{\psi} = i\frac{c}{B_0}\frac{\hat{\mathbf{e}}_{\parallel}\times\mathbf{k}_0\cdot\mathbf{k}}{k_{\perp}^2}(K_{-}^2\phi_{10+}\phi_{-} - K_{+}^2\phi_{10-}\phi_{+}), \tag{16}$$

where $\Gamma_{\mathrm{z}} = \mu_{\mathrm{i}}k_{\perp}^2$ and $K_{\pm}^2 = k_{\perp\pm}^2 - k_{\perp 0}^2$. Eliminating $\phi_{\pm}$ from (16) by using (15) we obtain the nonlinear dispersion relation

$$\omega + i\Gamma_{\mathrm{z}} = -\frac{c^2|\phi_{10}|^2}{B_0^2}\frac{|\hat{\mathbf{e}}_{\parallel}\times\mathbf{k}_0\cdot\mathbf{k}|^2}{k_{\perp}^2}\sum_{+,-}\frac{K_{\pm}^2}{D_{\pm}}, \tag{17}$$

which is the main result of this paper. It shows that zonal flows can be nonlinearly excited by marginally stable ETG modes in a non-uniform magnetoplasma. Here, $|\phi_{10}|^2 = \phi_{10+}\phi_{10-}$. Zonal flows are thus triggered and maintained if the ETG mode energy is pumped at a rate faster than the damping rate Γ_{z} of the zonal eddies.

4. Summary

To summarize, we have considered the nonlinear coupling between electrostatic ETG modes and zonal flows in a non-uniform plasma containing electron pressure and magnetic field inhomogeneities. A set of coupled equations for nonlinearly interacting ETG modes and zonal flows has been derived by using a hybrid approach in which the ions in the ETG modes are obeying a Boltzmann distribution, while the electron dynamics is governed by the electron continuity and energy equations with the appropriate electron fluid velocities in the drift approximation. The zonal flow is driven by the stresses of the ETG modes. The mode-coupling equations have then been Fourier decomposed to obtain the dispersion relation (17), which describes the generation of zonal flows by ETG modes due to modulational interactions, as suspected in [14]. In addition, we stress that our nonlinear equations (*viz.* (8), (9), and (12)) should be useful for investigating the evolution of nonlinearly coupled ETG modes–zonal flow turbulence. Finally, our investigation can easily be generalized to include the parallel electron dynamics in the presence of the magnetic vector potential of the toroidal ETG modes. The dispersion relation of the latter is then

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modified, and a new nonlinear driving term in the zonal flow equation would appear due to the nonlinear coupling of the parallel electron currents with the perturbed magnetic field.

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