*36th EPS Conference on Plasma Phys. Sofia, June 29 - July 3, 2009 ECA Vol.**33E**, P-2.197 (2009)*

Dynamics of Nonlinearly Interacting Magnetic Electron Drift Vortex Modes in a Nonuniform Plasma

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Abstract A simulation study of the dynamical evolution of nonlinearly interacting two-dimensional magnetic electron drift vortex (MEDV) modes in a nonuniform plasma is presented. Depending on the equilibrium density and temperature gradients, the system can be either stable or unstable. The unstable system reveals spontaneous generation of magnetic fields from noise level, and large-scale magnetic field structures are formed. When the system is linearly stable, one encounters MEDV mode turbulence in which there is competition between zonal flows and streamers. The MEDV turbulence exhibits non-universal (non-Kolmogorov type) and anisotropic spectra, and the formation of vortices and vortex pairs.

I. Introduction.

Early observations of spontaneously generated magnetic fields in laser-produced plasmas prompted the investigation of the magnetic electron drift vortex (MEDV) modes in a non-uniform plasma with the equilibrium density and electron temperature gradients. Later, the nonlinear model equations describing the dynamics of these modes in a nonuniform electron-ion plasma with fixed ion background have been formulated. In MEDV turbulence, the characteristic length scale of the system is the electron skin depth, while the typical frequency is thermal speed of electrons divided by the plasma inhomogeneity length scale.

The nonlinear study of turbulence in plasma physics is strongly related to the appearance of large-scale structures with higher symmetry, in contrast to the random underlying turbulence. The mechanism for generation of these motions with additional symmetry, frequently referred to as flows or structures (zonal flows and streamers), have been studied extensively in recent years. In a plasma allowing for inhomogeneities, the gradient specific modes known as drift-type modes are able to propagate in the direction perpendicular to the gradient. These modes can then spontaneously generate structures with higher symmetry, the large scale flows. Generation of these structures is commonly attributed to the effect of Reynolds stress (in a way similar to the hydrodynamics) induced by small-scale fluctuations using the free energy stored in density and temperature gradients. Once these structures are excited, they form an environment for the parent drift-type waves. Since the total wave energy is conserved and contains both the part stored in small as well as large structures, the parent waves and secondary flows (structures) form therefore a self-regulating system and cannot be addressed in isolation. This self-regulation can be described as drift waves and structures spectra as a coupled two-component turbulent system consisting of magnetic fluctuations and generated secondary flows. In this case the “slow” dynamics can be treated as a modulation of the high-frequency MEDV turbulence which simultaneously can exert significant stress on the structures.

In this paper, we present computer simulation studies of the nonlinear dynamics of the MEDV modes at different wave amplitudes including the strongly nonlinear regime where self-organization into localized vortices and vortex pairs takes place in the linearly stable regime. In the linearly unstable regime, we find the formation of large amplitude and large-scale (in comparison with the electron skin depth) magnetic fields. In the investigation of the spectral properties of the MEDV mode turbulence, we will define zonons (zonal flows) as nonlinear MEDV modes or structures with a finite scale (nonzero wave numbers) in the direction of the equilibrium density and temperature gradients, while streamers have a finite scale perpendicular to the density and temperature gradients.

II. Model nonlinear equations.

To derive the equations governing the nonlinear dynamics of 2D MEDV modes we assume an inhomogeneous electron plasma with immobile ions forming a neutralizing background and accept a geometry where the perturbed magnetic field is directed along the *z*-axis, so that $\mathbf{B} = B(x, y, t)\hat{\mathbf{z}}$, where $\hat{\mathbf{z}}$ is the unit vector along the *z*-axis, while the electric field and electron fluid velocity have vector components only in the $x-y$ plane, and thus all quantities vary only along the *x* and *y* coordinates. Then the electron dynamics is governed by the collisionless momentum equation and the energy equation. Assuming that the length scales of perturbations are much smaller than that of the background gradients and the equilibrium density n_0 and electron temperature T_0 depend only on the coordinate *x*, these equations can be reduced to the dimensionless form

$$\frac{\partial}{\partial t}\left(B - \nabla^2 B\right) = \left\{B, \nabla^2 B\right\} - \kappa_n B \frac{\partial B}{\partial y} - \frac{\partial T_1}{\partial y} \tag{1}$$

$$\frac{\partial T_1}{\partial t} = -\left\{B, T_1\right\} - \sigma \frac{\partial B}{\partial y} \tag{2}$$

where T_1 is electron temperature perturbation, coordinates and time are normalized by spatial and temporal scales of the system, the normalized background plasma gradients are given by $\kappa_n = \left(n_0'/n_0\right)\left(c/\omega_{pe}\right)$ and $\kappa = \left[(\gamma - 1) n_0'/n_0 - \left(T_0'/T_0\right)\right]\left(c/\omega_{pe}\right)$, where ω_{pe} is the electron plasma frequency, the primes denote differentiation with respect to x. The coordinate system is chosen such that $\kappa_n > 0$. With this normalization $\sigma = +1$ for $\kappa > 0$ and $\sigma = -1$ for $\kappa < 0$. Hence, the only parameters in the model equations are σ and κ_n, where σ only takes the two values +1 and -1.

Linearizing the model equations and assuming that B and T_1 are proportional to $\exp\left(ik_x x + ik_y y - i\omega t\right)$, we obtain the linear dispersion relation

$$\omega^2 = \frac{k_y^2}{1 + k^2}\sigma \tag{3}$$

where ω and $\mathbf{k} = \hat{\mathbf{x}}k_x + \hat{\mathbf{y}}k_y$ are the frequency and wave vector respectively. The dispersion relation predicts a purely growing instability for $\sigma = -1$ with nonzero k_y .

The presence of invariants of the nonlinear system is important in the analysis of the statistical behavior of MEDV mode turbulence. The model 2D MEDV equations (1) and (2) have at least two quadratic invariants. In the limit of small effects of the scalar nonlinearity, one of them is corresponding to the energy

$$\mathrm{E} = \mathrm{E}_B + \mathrm{E}_T = \iint \left[B^2 + (\nabla B)^2 \right] dxdy + \iint \frac{1}{\sigma} T_1^2 dxdy \tag{4}$$

where E_B is the magnetic energy and E_T is the energy of the temperature fluctuations, and the second one to the enstrophy

$$I = \iint \left(BT_1 + \nabla B \cdot \nabla T_1 \right) dxdy \tag{5}$$

of the system. Due to the presence of these two invariants, the double energy cascade is the characteristic property of the 2D MEDV mode turbulence.

III. Simulations results.

We have perpormed a set of simulations of the system (1) and (2) for different sets of parameters. The simulation code is based on a pseudospectral method to resolve derivatives in space with periodic boundary conditions, as outlined in [1], with random fluctuations as initial conditions.

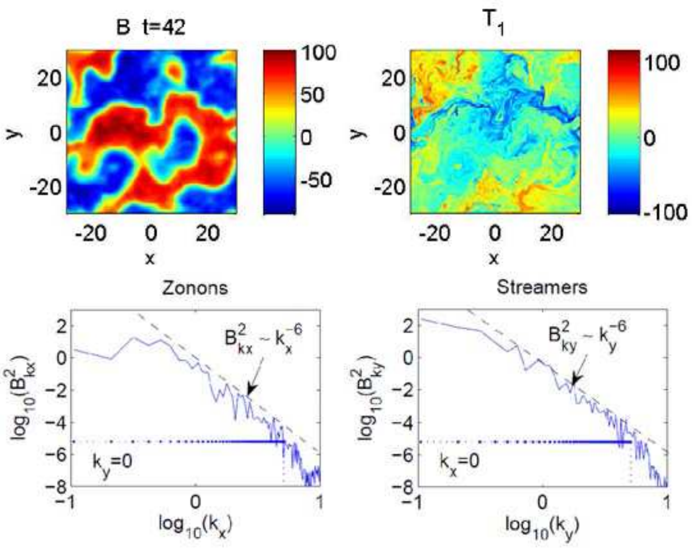

Figure 1: Linearly unstable regime. Top panels: Magnetic field and temperature fluctuations
Bottom panels: Zonon and streamer energy spectra of the magnetic field.

In the unstable regime ($\sigma = -1$), displayed in Fig. 1, we could observe magnetic field generation and the formation of large scale magnetic structures, accompanied by small-scale turbulence visible in the temperature fluctuations. The energy spectra are non-Kolmogorov and concentrated to streamers at small wavenumbers.

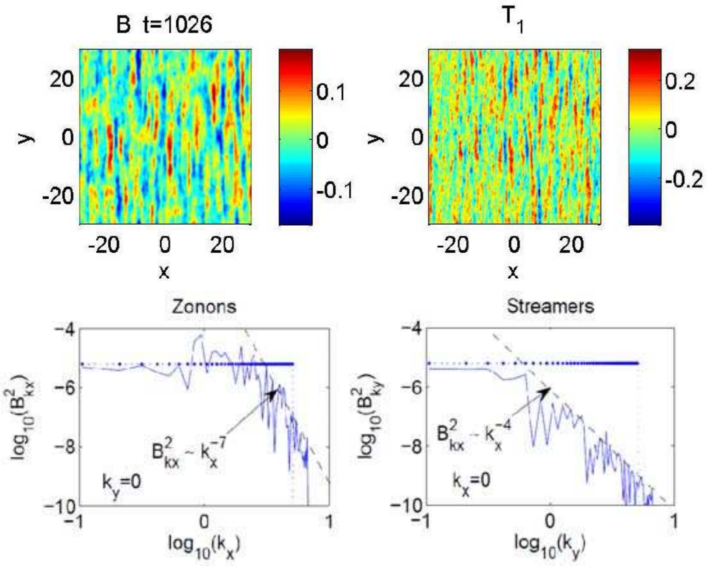

Figure 2: Linearly stable, small amplitude regime. Top panels: Magnetic field and temperature fluctuations Bottom panels: Zonon and streamer energy spectra of the magnetic field.

In the linearly stable regime ($\sigma = +1$) in Fig. 2, we observe small-scale turbulence and the formation of zero-frequency zonal flows (zonons). The energy spectra are strongly anisotropic with magnetic wave energy concentrated at zonons.

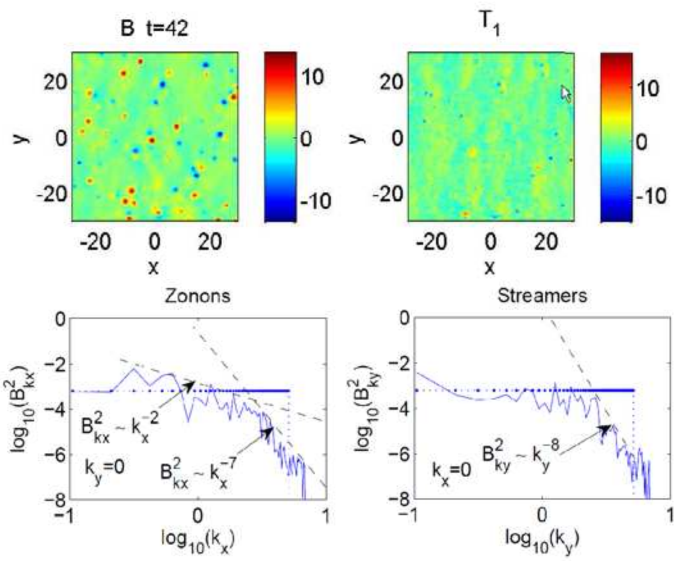

Figure 3: Large amplitude magnetic field fluctuations. Top panels: Magnetic field and temperature fluctuations. Bottom panels: Zonon and streamer energy spectra of the magnetic field.

In the large amplitude regime, illustrated in Fig. 3, with initial amplitude 10 times larger than in Fig. 2, we observe the formation of vortices and vortex pairs. The energy spectra of the magnetic field is anisotropic, where the energy is concentrated zonons.

Acknowledgment This work was supported by the European Communities under an association contract between EURATOM, and by the Swedish Research Council (VR).

[1] B. Eliasson, V. P. Pavlenko and P. K. Shukla, Phys. Plasmas **16**, 042306 (2009).