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Kinetic Theory and Simulation of Nonlinear Inertial Scale Magnetic Structures

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The origin of the fine-scale turbulence causing anomalous electron thermal transport in tokamaks is not yet fully understood. A related problem concerns the origin and formation of seed magnetic islands for the onset of neoclassical tearing modes. Observations indicate that tokamak plasmas with internal transport barrier(ITB) can have ion thermal transport reduced to neoclassical values but the electron thermal transport changes very little[1]. Recent studies of density fluctuations, using reflectometer measurements in the Joint European Torus(JET), indicate that after formation of the ITB, long wavelength modes are suppressed while high frequency short wavelength modes are unaffected[2]. One possible origin of these short wavelength modes is the electron temperature gradient-driven (ETG) instability which originates as a linearly unstable fluctuation above a certain critical electron temperature gradient[3]. There is recent evidence that electron thermal transport and temperature profiles are determined by a critical gradient length[4].

Another possible source of short wavelength fluctuations are nonlinear structures known as drift magnetic islands (DMI)[5-8]. Both the DMI and ETG modes have short scale lengths perpendicular to the equilibrium magnetic field; on the order of the electron collisionless skin depth which is smaller than the ion gyroradius in high temperature plasmas. The finite gyroradius effect produces a difference in the perpendicular drift between ions and electrons which induces a parallel current to sustain the island. The combination of a finite thermal gradient and negative tearing mode free energy parameter ($\Delta' < 0$) leads to the formation of an electron inertial scale DMI which is a coherent nonlnear magnetic structure[9].

The finite electron thermal gradient induces a real frequency and consequently a Landau resonance layer within the magnetic island for weak collisionality. In the sheared slab geometry the two-fluid[10] and gyrokinetic steady-state theory[11] for the isolated DMI has been compared to results from a gyrokinetic particle simulation of the growth and saturation of the DMI[12]. Inertial scale magnetic islands spontaneously formed with radial scale size and real frequency approximately in agreement with the theoretical analysis. The influence of shorter wavelength ETG modes was found to enhance the electrostatic zonal flow fields.

In this work we approach the DMI and ETG interaction problem using a low noise gyrokinetic paricle simulation model based on the perturbed distribution or δf-method [13]. This has allowed us to use much quieter intial conditions and examine more subtle effects of nonlinear interactions in more detail. Convergence studies with many particles have been made to understand the limits of the approach.

A preliminary test case is presented for the physical situation where a DMI with wavelength $k_y c/\omega_{pe} \leq 1$ evolves in a background of ETG fluctuations in the wavelength regime $\rho_e < k_y^{-1} < \rho_i$. We consider an isolated DMI centered on a mode rational surface, x_o, in a sheared slab equilibrium magnetic field given by $\mathbf{B} = B_o\hat{z} + \nabla A_z \times \hat{z}$ where $A_z = B_o(x - x_o)^2/2L_s$. The tearing mode parameter for this equilibrium is given by $\Delta' = -2k_y$. The equilibrium electron temperature and density profiles are taken to have constant gradient scale lengths, L_{Te} and L_n respectively, across the system. The value of $\eta_e = 10$ was used and $L_s/L_{Te} = 25$, $T_e/T_i = 4$, $m_i/m_e = 1837$, and $\rho_i = 4c/\omega_{pe}$.

Figure 1 shows the time evolution of the energy time histories. In the first phase of the time evolution the magnetic energy decreases and the electron kinetic energy increases as the inertial scale magnetic island is formed. In the second phase, the magnetic island then acquires a real frequency and the drift wave oscillations are observed at approximately $\omega \simeq \omega_{*e}(1 + \eta_e/2)$. The magnetic energy is then observed to increase to a steady value as well as the electron kinetic energy. The total electrostatic energy is also displayed and the ETG modes grow over the duration of the DMI evolution. The ETG mode growth reaches a sufficient amplitude to affect the electron dynamics in the region of the magnetic island. The result of the nonlinear interaction between DMI and ETG is a broadening of the initial magnetic island and this is seen in Figure 2. The contours of the vector potential show the magnetic field lines at two different time slices. The initial magnetic island width is approximately the electron collisionless skin depth, however, in the later phase of evolution it is 4-5 times larger. The steady state theory of the DMI without the background ETG turbulence predicts an island size of about the electron collisionless skin depth.

In conclusion, it is found that the DMI-ETG interaction can form broader magnetic island structures. These could evolve into coherent large scale neoclassical tearing modes or form radially overlapping magnetic islands centered on neighboring mode rational surfaces which result in an enhanced anomalous electron thermal diffusivity.

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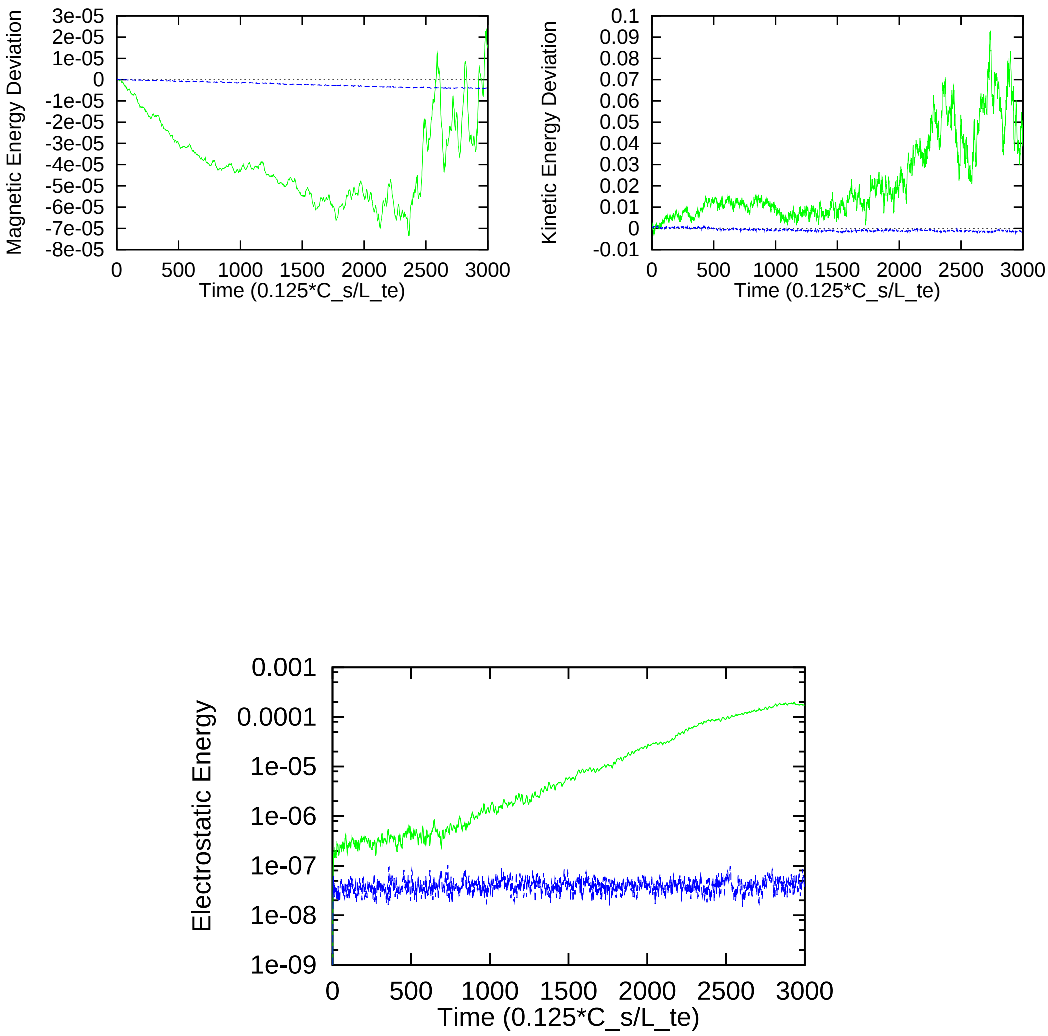

Figure 1: Energy time histories for the magnetic, kinetic and electrostatic components. Energy deviations are from the initial values. Green lines are for the $\eta_e = 10$ case and blue lines are for the case with no thermal or density gradients.

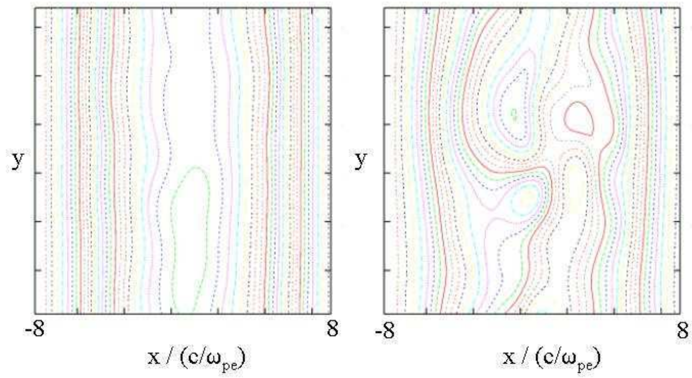

Figure 2: Contours of the perturbed magnetic vector potential taken at time 1000 (shown on the left) and 3000 (shown on the right). Rational magnetic surface, x_o, is located at x=0.

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