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GYROKINETIC SIMULATIONS OF ENERGETIC PARTICLE DRIVEN TAE/EPM TRANSPORT EMBEDDED IN ITG/TEM TURBULENCE

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Energetic particle (EP) transport from local high-n toroidal Alfvén eigenmodes (TAEs) and energetic particle modes (EPMs) has been simulated with the gyrokinetic code GYRO [1]. Linear and nonlinear simulations have identified a parameter range where the TAE and EPM are unstable alongside the well-known ion-temperature-gradient (ITG) and trapped-electron-mode (TEM) instabilities. A new eigenvalue solver in GYRO facilitates this mode identification. States of nonlinearly saturated local TAE/EPM turbulent intensity are identified, showing a "soft" transport threshold for enhanced energetic particle transport against the TAE/EPM drive strength parameter $[(n_{EP}/n_e)(T_{EP}/T_e)(R/L_{nEP})]$. The very long-wavelength TAE/EPM transport is likely saturated by nonlinear interaction with ITG/TEM-driven zonal flows. These fixed gradient length nonlinearly saturated states are accessible over a relatively narrow range of TAE/EPM drive strength. Within this range, and in the local limit employed, TAE/EPM driven transport more closely resembles driftwave microturbulent transport than "stiff" ideal MHD transport with a clamped critical pressure gradient. At higher critical drive strength, nonlinear saturation fails (EP transport increases without limit and background transport decreases). Presumably saturation is obtained by (quasi-linear) relaxation of the EP pressure gradient to this critical gradient.

Previously, GYRO was used to study turbulent transport of fusion-produced alpha particles from short-wave, electrostatic ITG/TEM turbulence [2]. The new work here treats EP transport from long-wave, EP-driven, Alfvénic TAE and EPM modes. Linear simulations, including a new GYRO eigenvalue solver, have been used to track local growth rates and frequencies of these local high-n instabilities. Nonlinear simulations track the induced energy and particle transport in all species. All simulations are local, which is appropriate for sufficiently small $\rho_*=\rho_s/a$ where $\rho_s=c_s/\Omega_{ci}$ is the ion sound gyroradius and a is the plasma radius. The short-wave ITG/TEM modes, whose driving gradients are kept in the simulation, are on the scale ρ_s. A radial density gradient in the sparse EP population drives TAE/EPM modes at much longer length scales — on the order of ρ_{EP}, the EP gyroradius. Figure 1 shows the $k_\theta=nq/r$ spectrum of rates.

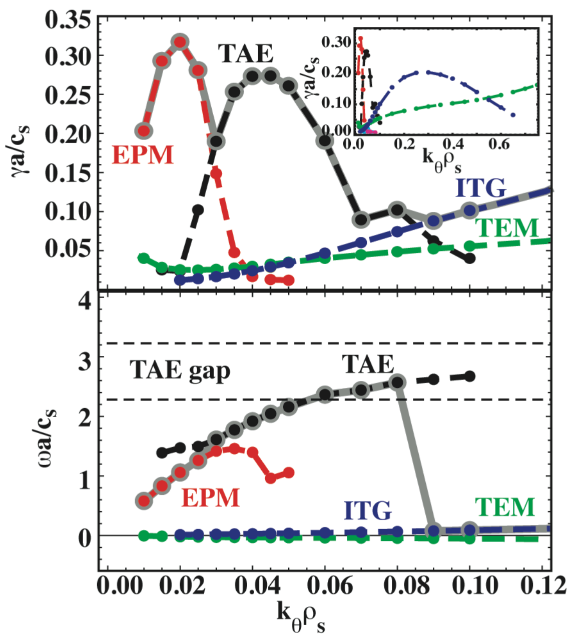

Fig. 1: Linear frequency ω and growth rate γ for leading local modes with q=2, s=1, r/a=0.5, R/a=3, $T_i=T_e$, $T_{EP}=100T_e$, $n_{EP}=0.025n_e$, $a/L_{Ti}=a/L_{Te}=3$, $a/L_{ni}=a/L_{ne}=1$, $a/L_{nEP}=4$, $a/L_{TEP}=0$. Inset shows same data over a greater range.

The TAE and EPM are simultaneously destabilized primarily by the EP spatial pressure gradient. Reduction of the background ion and electron gradients with fixed magnetic geometry (circular s-α with α=0) modestly lowers TAE/EPM growth rates. All length scales contribute to EP transport. However, as EP energy increases large perpendicular EP orbits partially average out ITG/TEM fluctuations, decreasing transport [2]. EP transport from long-wavelength TAE/EPM fluctuations shows no such reduction.

Nonlinear simulations of 40 interacting modes were performed over a range of EP drive strengths, represented by the relative EP density n_{EP}/n_e. A clear onset of TAE/EPM fluctuations is observed as n_{EP}/n_e increases (Fig. 2). At sufficiently weak n_{EP}/n_e drive, a state of finite saturated TAE/EPM intensity can be found in GYRO. The nonlinear saturation mechanism is interaction of finite-k_θ fluctuations with sheared k_θ=0 zonal flows. These zonal flows are driven primarily by ITG/TEM transport, and the system fails to saturate when ITG/TEM turbulence is reduced either by reduction of background gradients or exclusion of modes in the ITG/TEM range. Systems with stronger TAE/EPM drive (n_{EP}/n_e > 0.8%) also fail to nonlinearly saturate for the parameters given. Proximity to the high-n ideal MHD ballooning mode stability limit, and the related "sub-critical" limit in GYRO [3], is a likely component in this failure to saturate in this particular case.

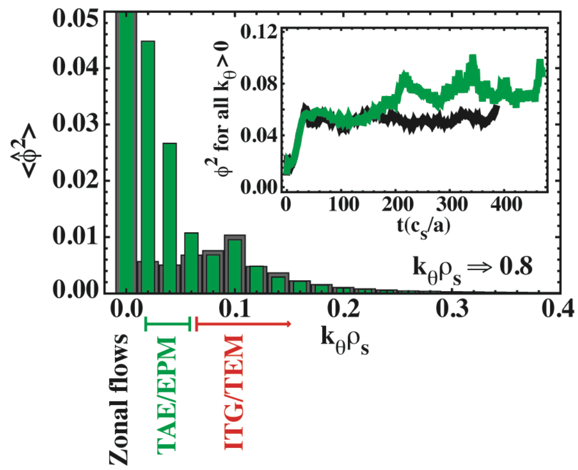

Fig. 2: Time averaged fluctuation intensity per mode for n_{EP}/n_e=0.5% (below TAE/EPM threshold, black) and n_{EP}/n_e=0.8% (above TAE/EPM threshold, green). All other parameters the same as Fig. 1. Inset shows time traces of total finite-k_θ fluctuation intensity.

In the range where fixed gradient length nonlinear saturation is obtained, the onset of TAE/EPM transport is not "stiff." Figure 3 shows a modest slope in the gyroBohm scaled EP diffusion coefficient with TAE/EPM drive strength (n_{EP}/n_e above 0.5%) corresponding to a stiffness of $S = 1 + d\ln \mathrm{D}_{\mathrm{EP}}/d\ln z = 1.5$. Unlike the ideal MHD high-n ballooning mode onset, the high-n local EP-driven TAE/EPM threshold does not appear to impose a clamped EP critical pressure gradient. At a higher and critical drive strength [n_{EP}/n_e above 0.8%] fixed gradient nonlinear saturation fails (EP transport increases without limit and background plasma transport actually decreases) and presumably the EP driving gradient relaxes to this critical EP pressure gradient.

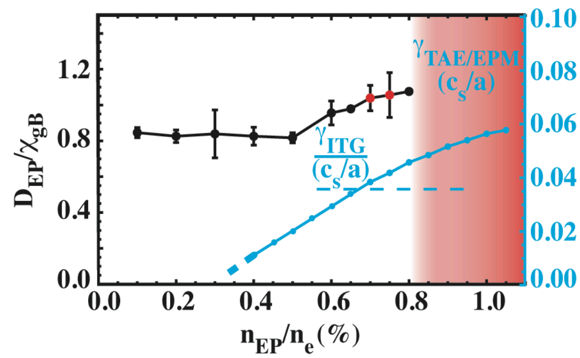

Fig. 3: GyroBohm scaled diffusion coefficient of energetic particle density $\mathrm{D}_{\mathrm{EP}}/\chi_{\mathrm{gB}}$ vs. TAE/EPM drive strength parameter (black curve). Low-k_θ linear growth rates shown for comparison (blue, right axis). Red dots and shaded areas had runaway at long times. Parameters same as in Fig. 1.

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