Nonlinear Simulations of Drift-Wave Turbulence in Alcator C-Mod

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Abstract: We present turbulence simulations of transport that are compatible with measurements in the core of typical H-mode plasmas in Alcator C-Mod. Our two-species nonlinear gyrokinetic simulations of turbulent transport due to long wavelength electrostatic drift-type instabilities employ a flux-tube domain based on a realistic non-circular magnetic geometry. These simulations with GS2 differ from previous work by including both non-adiabatic electron effects and finite collisionality. The results reconcile theory and experiment by means of a nonlinear upshift of the effective critical gradient. This upshift is not present in otherwise identical simulations with the collisionality lowered to a level that is typical of most other tokamaks. An upshift can be recovered at low collisionality if kinetic electron effects are ignored by using an adiabatic electron treatment - a simplification made in previous reports of such an upshift - but the transport in the region above the effective critical gradient is less stiff than with the more complete kinetic treatment at the actual C-Mod collisionality. We conclude that it is important to include both collisions and non-adiabatic electron effects in simulations of turbulent transport in tokamaks.

1. Introduction

The failure [1] of several otherwise successful transport models to accurately predict plasma temperatures in Alcator C-Mod [2] prompted us to examine whether more fundamental simulations for C-Mod conditions can close the gap between theory and experiment. The failure of the IFS-PPPL transport model [3], in particular, might simply be due to the high collisionality of Alcator C-Mod plasmas, which is outside the collisionality range of the simulations that form the foundation of that model. Changing the model by reducing the diffusivity by an overall factor of 1/3 is not enough, but increasing the critical gradient by 50-75% is sufficient to produce the measured temperatures. The focus of our investigation is therefore on errors in the model's formulation of the critical gradient. New linear stability calculations for the C-Mod conditions have a critical gradient that is somewhat higher than predicted by the IFS-PPPL model, but it remains well below the measured temperature gradients so a nonlinear process seems to be required.

A possible resolution of the discrepancy is a nonlinear upshift of the effective critical gradient [4]. It is known that turbulence driven 'zonal' flows are excessively damped in the gyrofluid simulations that formed part of the foundation for the IFS-PPPL model. As a result, the over-damped zonal flows are less capable of limiting the turbulence and the model produces no nonlinear upshift [4]. However, collisions have been shown to damp zonal flows [5, 6], and Alcator C-Mod plasmas are very collisional so the upshift might be effectively eliminated. The reality of a nonlinear upshift might be challenged more generally because the inclusion of electron dynamics [7] leads to a large increase in transport above that predicted by earlier simulations with adiabatic electrons (i.e., those in Ref. 4).
We are led, then, to compare experiment with nonlinear gyrokinetic simulations of H-mode plasmas in Alcator C-Mod to address directly whether drift-type instabilities could be responsible for the observed transport. The nonlinear gyrokinetic simulations of turbulent

transport described below extend previous work on long wavelength ($k_\perp \rho_i < 1$) electrostatic drift-type instabilities by including both non-adiabatic kinetic electron effects and finite collisionality in realistic noncircular geometry. These simulations are indeed characterized by a nonlinear upshift of the effective critical gradient that may reconcile theory with experiment. Parameters typical of H-mode plasmas in Alcator C-Mod are used in most simulations, but we find that lower collisionality (typical of other tokamaks) produces little or no upshift.

2. Plasma Conditions and Simulation Method

The plasma parameters used in this work are typical of ICRF heated EDA H-mode plasmas in Alcator C-Mod., with I_p=1.0 MA, R_o=0.67 m, B_o=5 T, $\overline{n}_e$=3.5x10^{20} m^{-3}. The simulations are located at r=0.56a, with r/R=0.179, T_e=1.5 keV, q=1.3, κ=1.28, δ=0.12. In C-Mod the ion temperature is infrequently measured near r=a/2, but there are many plasmas with measurements of the central ion temperature (from Argon X-ray spectra and fusion neutron production) which show that $T_i(0)$~$T_e(0)$. Power balance calculations compatible with the measured central ion temperature produce T_i~T_e in the colder outer regions also (where temperature equilibration is stronger), but there is no direct T_i measurement there. In comparisons with measured temperatures we assume that T_i=T_e everywhere.

We show below that the critical temperature gradient depends on the magnetic shear, $\hat{s}$, which is not well determined in C-Mod. The EFIT code [8] has been used to calculate the magnetic geometry, but the results near r ~ a/2 are rather uncertain because there is little internal data available for constraining the calculation. Sawteeth are present in the discharges we are modeling so we have required that 0.85 ≤ q(0) ≤ 0.90. In other tokamaks with measured q profiles the sawtooth-mixing inversion radius is seen to be close to the q=1 radius. The inversion radius determined from ECE T_e measurements is near r=6 cm in these plasmas, so we have accepted only those EFIT solutions with 5 cm ≤ $r_{q=1}$ ≤7 cm. A constraint on the average current density just outside the q=1 location is used to vary the q and $\hat{s}$ at r~a/2. We find that EFIT solutions can provide a good fit to the magnetic data (χ^2 ~ 9.5-10.5) for a wide range of q and $\hat{s}$ values at r=0.56a: 1.17≤q≤1.5 and 0.7≤$\hat{s}$≤1.3. (An MSE diagnostic is now taking data and should provide constraints on the internal magnetic geometry.)

We present results from drift-wave turbulence simulations by GS2 [9], a time dependent, high-n, gyrokinetic stability code that uses an implicit initial-value algorithm. This code has been benchmarked extensively [9, 10, 11] with the FULL code [12]. The code employs a non-circular flux-tube geometry and a momentum-conserving Lorentz collision operator, and includes non-adiabatic kinetic effects for both electrons and ions, as well as electromagnetic effects. We typically use a Miller local equilibrium, but similar results for C-Mod have been obtained using an EFIT equilibrium.

The present work is based largely on electrostatic drift-type instabilities with long wavelength ($k_\perp \rho_i < 1$). Linear simulations including electromagnetic terms indicated that their effects are not large (local β=0.8%.) Most of the nonlinear simulations use two species: electrons and deuterium. A simulation with carbon raising Z_{eff} to 1.5 differed rather little from its Z_{eff} =1.0 counterpart. Most simulations include a kinetic treatment of both the electrons and ions, and include finite collisionality. In order to relate the results to prior work, some simulations have used lower collisionality, and some have used an adiabatic treatment of the electrons.

Most of the nonlinear simulations use a computational domain with dimensions of 38 ρ_i and 26 ρ_i in the poloidal and radial directions, respectively, where the flux tube crosses the outer midplane. The 4 values of k_y and 23 values of k_x are spaced evenly in the ranges $0 \le k_y \le 0.50$ and $-2.73 \le k_x \le 2.73$. The highest resolution simulations use a computational domain with dimensions of 75 □$_i$ and 72 □$_i$ in the poloidal and radial directions, respectively, where the flux tube crosses the outer midplane. The 7 k_y and 71 k_x are spaced evenly in the ranges $0 \le k_y \le 0.50$ and $-3.04 \le k_x \le 3.04$.

3. Results of Nonlinear Gyrokinetic Simulations

Nonlinear simulation results are shown in Fig. 1a together with the conducted power predicted by the IFS-PPPL model, which predicts a power flow greatly exceeding the total heating power for values of R/L_T near the measured range. In the nonlinear simulations as the temperature gradient increases just above the linear stability threshold the energy transport rises slowly, but eventually it rises steeply at higher R/L_T – as in previous reports of a nonlinear upshift of the critical gradient. The upshift leads to consistency between the available heating power and the predicted transport for simulations with $\hat{s}=1.2$ and values of R/L_T in the lower part of the measured range. A few high-resolution simulations confirm the lower resolution results. The existence of an upshift in the critical gradient is also seen for lower magnetic shear, but the agreement with experiment is not good with such low shear.

Including collisions is important because they are known to damp zonal flows; this damping is particularly important near marginal stability, with nonlinear damping becoming more important as both the turbulence and zonal flow amplitudes grow with increasing temperature gradient. Simulations near marginal stability show that collisional flow damping does increase the predicted transport in the region where collisionless simulations predict near total suppression of transport [6]. Extrapolation to the high collisionality of Alcator C-Mod plasmas might have effectively eliminated the upshift, but we find that is not the case.

Simulations with five times lower collisionality (more typical of tokamaks such as AUG, DIII-D, JET, JT-60U, and TFTR) are qualitatively different (Fig. 1b). While lowering the ion collisionality has little effect, reducing the electron collisionality largely removes the nonlinear upshift. Apparently, the high collisionality of C-Mod is sufficient to suppress the

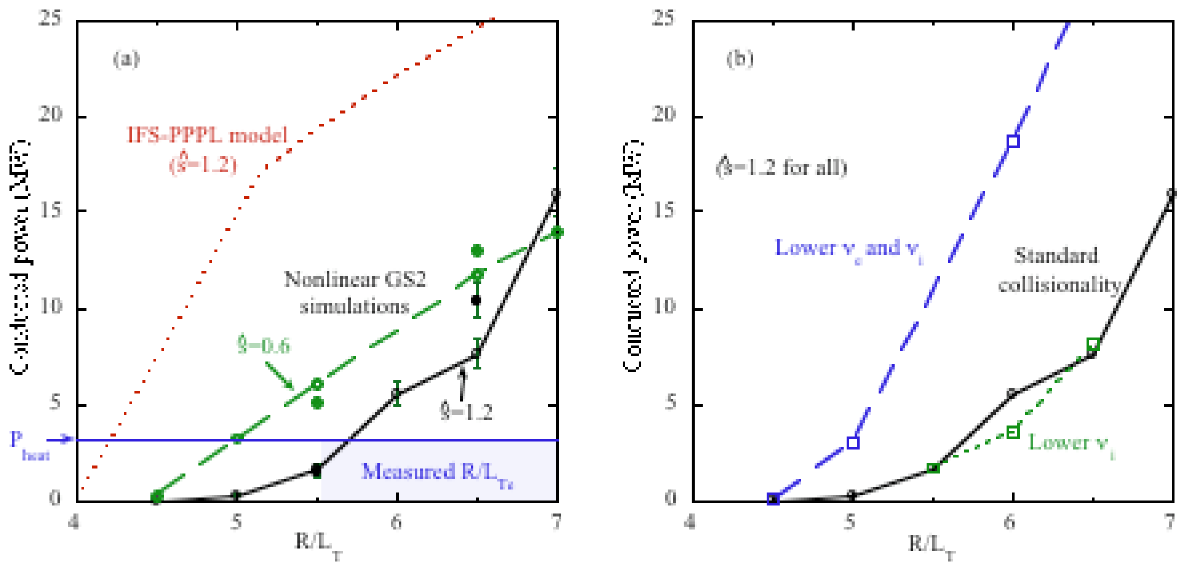

Fig. 1 a) Power flow vs. R/L_T *for IFS-PPPL model and GS2 simulations with* $\hat{s}=0.6$ *and 1.2, filled symbols denote high-resolution results, open symbols for low resolution. b) Power flows for standard* $\hat{s}=1.2$ *case and with collisionalities reduced by a factor of 5.*

electron kinetic effects nearly to the adiabatic-electron limit. This change may explain why the IFS-PPPL model's predictions for TFTR [3] and JT-60U [13] are generally successful, although the model usually fails for Alcator C-Mod plasmas. Simulations with adiabatic electrons have a larger upshift and predict lower transport than the simulations of Fig. 1a, while there is no pronounced overall dependence on collisionality; however, at the lowest value of R/L_T simulated the transport does increase with collisionality, so these results may be qualitatively consistent with previous work [6]. We find that simulations with adiabatic electrons underestimate the transport, as reported elsewhere [7]. This indicates that previous works' omission [4] of kinetic electron effects and collisions was seriously incomplete.

At low collisionality, trapped electrons contribute significantly to the linear growth rate of microinstabilities, as is well known [12]. In the present case, lowering the collisionality doubles the linear growth rate of the ITG instabilities that dominate the system. This strongly reduces the Dimits shift by reducing the 'window' of zonal flows that are capable of stabilizing the linear modes while themselves remaining stable to small perturbations. Direct numerical analysis indicates this is mainly because stronger sheared zonal flows are required to stabilize the linear instabilities at low collisionality. The stability of the zonal flows to a tertiary instability [14] does not seem to be sensitive to the collisionality.

Nonlinearly, low collisionality also allows the trapped electron nonlinearity to become important [15, 16, 17]. This nonlinearity particularly affects the development of finite $k_x \rho_i$ perturbations (i.e., modes which 'balloon' at positions other than the outboard midplane) and allows more interactions to exist between the dominant linear instabilities and the zonal flows.

The relative importance of the increased linear drive and the non-adiabatic electron nonlinearity has not yet been conclusively determined in our simulations, but is actively being studied.

This picture is further complicated by some recent results of nonlinear GS2 simulations of a lower collisionality DIII-D plasma [18]. Most of the DIII-D simulations also include non-adiabatic electrons and finite collisionality, and they may exhibit some nonlinear upshift. Nevertheless, the predicted transport and fluctuation level is 3-4 times higher than the experimental values. Interestingly, simulations with adiabatic electrons are in closer agreement with experiment. This prompts a speculation that deserves further study: electron temperature fluctuations may drive ETG modes unstable, and one effect of the ETG turbulence may be to reduce the Te fluctuations and reduce their contribution to ITG/TEM transport. Thus, the approximation of adiabatic electron response may not be entirely artificial in some low collisionality cases.

4. Summary

While the IFS-PPPL model does not agree with typical H-mode transport in Alcator C-Mod tokamak, more fundamental nonlinear gyrokinetic simulations of turbulent transport caused by long wavelength toroidal drift-type instabilities are shown to be compatible with the available measurements. This agreement is achieved because the effective critical gradient is moved beyond the linear stability point. We interpret this as the first experimental confirmation of the prediction [4] that nonlinear processes lead to an upshift.

In addition, we have shown the importance of including both collisions and non-adiabatic electron effects. In particular, our simulations with lower collisionality indicate that omission of kinetic electron effects makes previous work [4] seriously incomplete (also suggested by the results of Ref. 7). With finite collisionality more typical of most other tokamaks, non-adiabatic electron effects appear to be responsible for eliminating the upshift. The upshift survives when the collisionality becomes large enough to recover adiabatic electron behavior, but an upshift may not be present in most tokamaks.

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References

[1] MIKKELSEN, D.R., et al., "Tests of 1-D Transport Models, and their Predictions for ITER", (proc. 17th Int. Conf. Yokohama, 1998) C&S Papers Series No. 8/C, IAEA, Vienna (2001), CD-ROM file ITERP1-08.
[2] GREENWALD, M., et al., Nucl. Fusion **37** (1997) 793.
[3] KOTSCHENREUTHER, M., DORLAND, W., BEER, M.A., HAMMETT, G.W., Phys. Plasmas **2** (1995) 2381.
[4] DIMITS, A., et al., Phys. Plasmas **7** (2000) 969.
[5] HINTON, F.L., and ROSENBLUTH, M.N, Plasma Phys. Control. Fusion **41** (1999) 41.
[6] LIN, Z., HAHM, T.S., LEE, W.W., TANG, W.M., WHITE, R.B., Phys. Plasmas **7** (2000) 1857.
[7] CHEN, Y., PARKER, S., Phys. Plasmas **8** (2001) 2095.
[8] LAO, L. ST. JOHN, H., STAMBAUGH, R.D., KELLMAN, A.G., PFEIFFER, W., Nucl. Fusion **25** (1985) 1611.
[9] KOTSCHENREUTHER, M., REWOLDT, G., TANG, W.M.., Computer Phys. Comm. **88** (1995) 128.
[10] BELLI, E., DORLAND, W., HAMMETT, G.W., ZARNSTORFF, M., Bull. Am. Phys. Soc. **46** (2001) 232, paper LP1 77.
[11] BOURDELLE, C., et al., Bull. Am. Phys. Soc. **46** (2001) 137 paper GO1 4.
[12] REWOLDT, G., and TANG. W.M., Phys. Fluids **B2** (1990) 318.
[13] MIKKELSEN, D.R., et al. "Correlation Between Core and Pedestal Temperatures in JT-60U",(proc. 18th Int. Conf. Sorrento, 2000) C&S Papers Series No. 8/C, IAEA, Vienna (2001), CD-ROM file EXP5/20.
[14] ROGERS, B.N., DORLAND, W., KOTSCHENREUTHER, M., Phys. Rev. Letters **85** (2000) 5336.
[15] CHEN, L., et al., Phys. Rev. Letters **39** (1977) 754.
[16] HAHM, T.S., and TANG, W.M., Phys Fluids **B3** (1991) 989.
[17] HAHM, T.S., Phys. Fluids **B3** (1991) 1445.
[18] ROSS, D.W., DORLAND, W., "Comparing simulation of plasma turbulence with experiment II: gyrokinetic simulations", to appear in Phys. Plasmas (2002).