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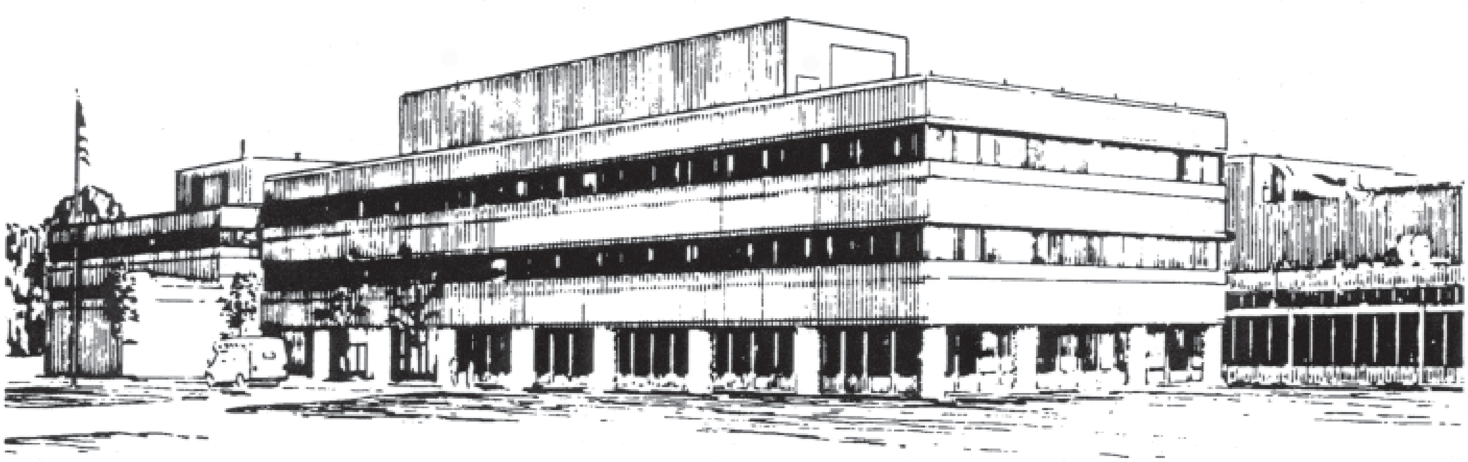

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Benchmarking Nonlinear Turbulence Simulations on Alcator C-Mod

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Linear simulations of plasma microturbulence are used with recent radial profiles of toroidal velocity[1] from similar plasmas to consider nonlinear microturbulence simulations and observed transport analysis on Alcator C-Mod[2]. We focus on internal transport barrier (ITB) formation in fully equilibrated H-mode plasmas with nearly flat velocity profiles. Velocity profile data, transport analysis and linear growth rates are combined to integrate data and simulation and explore the effects of toroidal velocity on benchmarking simulations. Areas of interest for future nonlinear simulations are identified. A good gyrokinetic benchmark is found in the plasma core, without extensive nonlinear simulations.

RF-heated C-Mod H-mode experiments [3,4], which exhibit an ITB, have been studied with the massively parallel code GS2 [5] towards validation of gyrokinetic microturbulence models. New, linear, gyrokinetic calculations are reported and discussed in connection with transport analysis near the ITB trigger time of shot #1001220016 (Fig. 1).

I. Linear gyrokinetic simulations of ITG/TEM and ETG drift modes

Earlier work [6] has been recomputed and verified using TRXPL software, which produces input files for GS2 from TRANSP analysis. As was found from the earlier simulations, the linear gyrokinetic simulations generally support the picture of ion/electron temperature gradient (ITG/ETG) microturbulence driving high χ_i/χ_e and that stable ITG correlates with reduced particle transport and improved χ_i on C-Mod. Only radii at r/a=0.25, 0.45 and 0.65 are examined. No strongly growing modes are found linearly unstable in the plasma core. In the plasma core weakly unstable ITG range drift modes occur for simulations of five 2π field periods along the field line, but these instabilities arise from boundary conditions: γ^{lin} in the ITG range decreases to 0.002 MHz when the field lines are extended to seventeen 2π field periods. Figure 2 shows ITGs destabilized at, as well as outside, the ITB region with γ^{lin} in laboratory units. As before [6], ETGs are strongly unstable at and outside the ITB, with γ^{lin}=1.9 MHz and 2.5 MHz. Initial nonlinear calculations [7] in the ITG-TEM range of wavelengths for C-Mod confirm the linear simulations, which predicted reduced

ITG instability inside the ITB region before formation, without invoking ***E*×*B*** shear suppression of turbulence [8].

II. Toroidal rotation suppression of microturbulence: comparison to transport analysis

Thermal diffusivities from nonlinear microturbulence simulations outside the barrier region may be modified with the Waltz prescription [8] for ***ExB*** shear corrections, making use of the linear growth rates. The approximate Waltz quench rule for reduction of nonlinear ITG drift-wave diffusion by ***ExB*** shear compares the maximum rates of linear growth to the toroidal velocity shearing, leading to a transport reduction factor *K* [9]. $\chi=K\chi_{GS2}=\chi_{GS2}[1-Min\{1,G|\gamma_{ExB}/\gamma^{lin}_{ITG}|\}]$, where $0.3<G<3.0$ and $\gamma_{ExB}=R\ (B_\theta/B)\ d/dr[V_{tor}/(R_o+r\cos\theta)]$ [10]. This formulation neglects v_{pol} and P. A more accurate treatment is possible with the GYRO flux-tube code [11], which incorporates toroidal velocity shear along with evolving zonal flows.

We show in Fig. 3 recent velocity measurements [1] from ITB cases similar to the one simulated with GS2, In the simulated shot the core velocity at the trigger time was measured to be zero. In general, ITBs form from fully equilibrated EDA H-mode plasmas, yet the recent velocity measurements from [1] are representative of averaged plasma conditions which differ in important ways from the shot simulated. The *v(r)* data do not show the central velocity decreasing through zero during the H-mode to ITB phase. When $v_{tor}(0)=0$ at 1.05 sec the central plasma pressure is 0.19 MPa and the plasma has a fully developed ITB. Fully equilibrated EDA H-mode plasmas are seen to exhibit flat velocity profiles on C-Mod. In H-mode near 0.9s error bars on the toroidal velocity are typically ±10% within and at the ITB region, and ±20% outside. In Figure 3 are shown extrapolations of the measured core velocity data for the simulated shot. A flat profile with $v_{tor}(0)=0$ is shown at 0.25*r*/*a*, 0.45*r*/*a* and 0.65*r*/*a* (open squares). Maximum velocity shearing rates are found from the blue squares, and error bars of $\pm0.1\times10^4$m/s within and at the ITB region and $\pm0.2\times10^4$m/s outside the ITB.

A good quantitative benchmark of gyrokinetics is possible in the core, since there v_{tor} is zero and it is likely that the velocity shear is zero. In Fig. 4 are shown χ_{eff} from transport analysis and $\chi_i^{Chang\text{-}Hinton}$. At C-Mod's high density, χ_{eff} is more accurately known than χ_e and χ_i. Simulations are compared to χ_{eff} rather than the nonequilibrium, heat pulse $\chi_{\square}^{hp}$ [4]. No anomalous transport is found in the core, consistent with simulations which show no strongly unstable linear microstabilities there. Gyrokinetic calculations are unlikely to yield significant nonlinearly destabilized turbulence in the core, given the flat density and temperature profiles. Self-sustained drift wave turbulence is not likely; the collisionality $C\sim10^{-3}<<1$ [12].

In Table I are compared the maximum linear growth rates of ITG instabilities, the ***ExB*** shearing rates and the Waltz quench factors, *K* for the extrapolated open and blue square data points, based on equilibrated H-mode plasmas (Fig. 3) as discussed above. ***ExB*** shear suppression is subdominant except possibly in the ITB region.

Fully equilibrated, EDA H-mode plasmas on C-Mod, from which ITBs develop, exhibit nearly flat *v(r)*. At the trigger time (0.9s) of the shot simulated, *v(0)* is known to be zero, Hypothesizing $v_{tor}(r)=0$, nonlinear flux-tube simulations could be quantitatively benchmarked against transport analysis for this experiment outside the ITB region, without the inaccuracies inherent in calculations which do not include zonal and ***ExB*** flow selfconsistently. ***ExB*** shear suppression may be important in benchmarking the gyrokinetic model against experiment in the ITB region. While linear simulations provide a good model benchmark in the plasma core, nonlinear ITG and ETG simulations are still essential for experimental validation of the gyrokinetic drift wave model at and outside the ITB.

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Table I. ***ExB*** suppression factors *K (G=1)* for open and blue squares (*), Fig. 3.

r/a	γ^{lin}_{ITG}	γ_{ExB}	γ_{ExB}*	$\gamma_{ExB}/\gamma^{lin}_{ITG}$	$\gamma_{ExB}/\gamma^{lin}_{ITG}$*	*K*	*K**
0.25	0	0	$0.6x10^4$/s	0	--	1	1
0.45	$2.6x10^4$/s	0	$1.4x10^4$/s	0	0.5	1	0.5
0.65	$13x10^4$/s	0	$1.5x10^4$/s	0	0.1	1	0.9

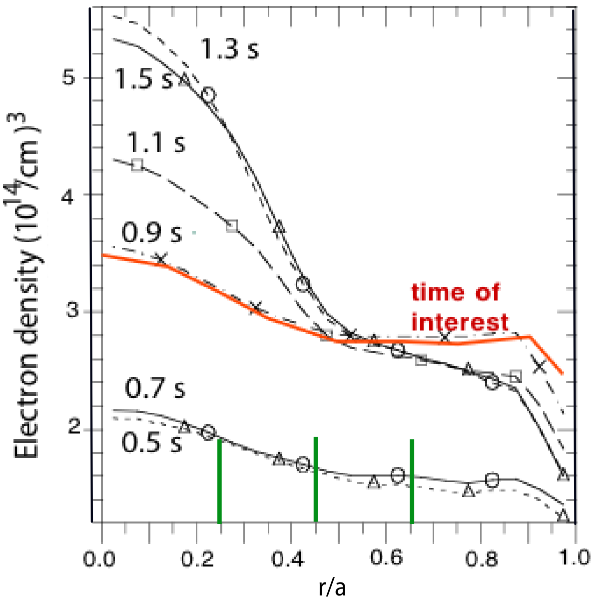

Figure 1. Evolution of electron density profile

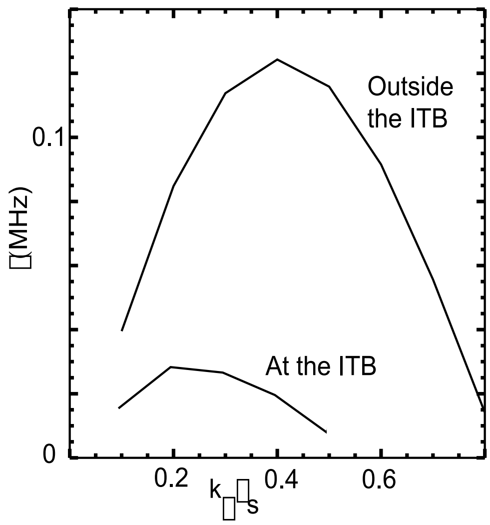

Figure 2. Linear growth rates of ITG modes at and outside ITB

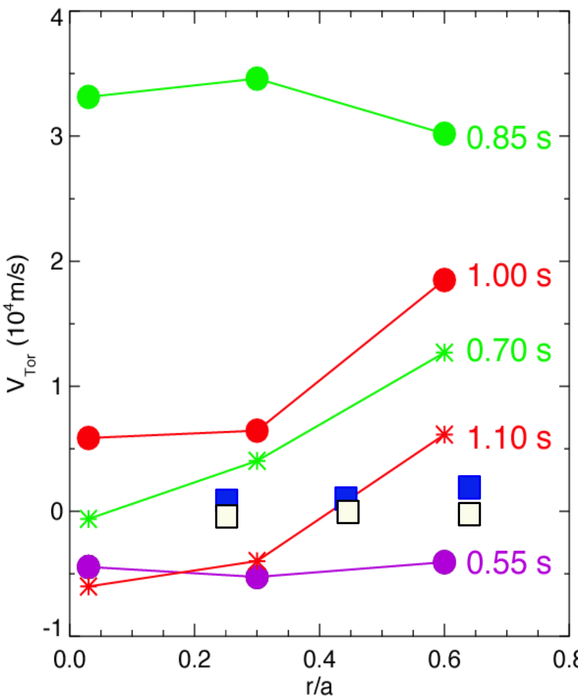

Figure 3. Toroidal velocity data, and extrapolations for shot simulated with flat v(r) profile (open squares) and maximum shearing rates (blue squares).

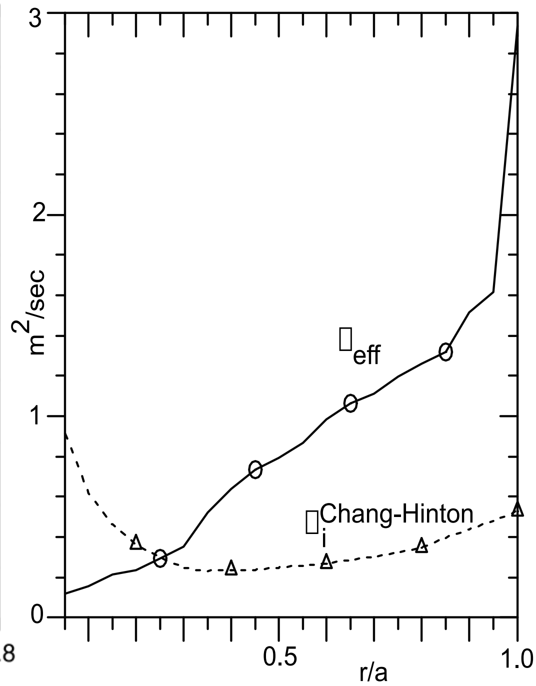

Figure 4. Radial profiles of □$_{eff}$ and Chang-Hinton neoclassical ion conductivity.

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