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Testing Gyrokinetics on C-Mod and NSTX

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Quantitative benchmarks of computational physics codes against experiment are essential for the credible application of such codes. Fluctuation measurements can provide necessary critical tests of nonlinear gyrokinetic simulations, but such require extraordinary computational resources. Linear microstability calculations with the GS2 [1] gyrokinetic code have been carried out for tokamak and ST experiments which exhibit internal transport barriers (ITB) and good plasma confinement. Qualitative correlation is found for improved confinement before and during ITB plasmas on Alcator C-Mod [2] and NSTX [3] with weaker long wavelength microinstabilities in the plasma core regions. Mixing length transport models are discussed. The NSTX L-mode is found to be near marginal stability for kinetic ballooning modes.

Fully electromagnetic, linear, gyrokinetic calculations of the Alcator C-Mod ITB during off-axis rf heating, following four plasma species and including the complete electron response show ITG/TEM microturbulence is suppressed in the plasma core and in the barrier region before barrier formation, without recourse to the usual requirements of velocity shear or reversed magnetic shear [4-5]. No strongly growing long or short wavelength drift modes are found in the plasma core but strong ITG/TEM and ETG drift wave turbulence is found outside the barrier region. Linear microstability analysis is qualitatively consistent with the experimental transport analysis, showing low transport inside and high transport outside the ITB region before barrier formation, without consideration of ***ExB*** shear stabilization.

Calculations of the ITG mode instability threshold and the dependence of instability on temperature and density scaling length have been used to test the GS2 gyrokinetic model for ITG microturbulence on C-Mod [4-5]. Transport analysis at the ITB onset time in H-mode experiments [6] is in rough agreement with the linear mixing length model $\gamma/\langle k_\perp^2 \rangle$. The mixing length estimates exceed experimental estimates of transport by less than a factor of two and are in agreement with experiment in the plasma core (see Table I). GS2

calculations were also used to verify an algebraic, computationally-based model for the ITG instability threshold [7] and standard analytic models [8, 9]. Agreement of these threshold models (within 40%) with the critical temperature threshold obtained with the more complete physics of the GS2 code verifies that these standard models are approximately correct. Figure 1 shows a phase diagram for ITG/TEM instability for C-Mod at ITB onset in the barrier region on which are mapped the locations for linear GS2 calculations. The topology of the diagram, adapted from Ref. 10, is preserved but for this case, the critical ITG temperature threshold is 6.9, rather than 2.5 as in Ref. 10. Considering experimental errors of 10-20%, and even larger errors in plasma gradients, these differences are not remarkable.

Definitive testing of gyrokinetics is much more difficult for NSTX than for C-Mod, since the potentially most dangerous, long wavelength modes are not ITG/TEM only. The new microtearing modes may cause significant transport. NSTX L-mode plasmas are found to exhibit improved electron transport [11] and less strongly destabilized microtearing than do H-modes. ETG and microtearing modes dominate in different regions of NSTX plasmas and so appear to compete for the same free energy source. Further, new calculations show that L-mode plasma is just below the critical threshold for kinetic ballooning modes (Fig. 2). The linear microstability of a slow current ramp, low density L-mode pulse #112996 was studied at a selected radius, r/a=0.55, using an equilibrium based on experimental data. At this radius, where the local beta is 9%, the ITG/TEM modes are unstable, and the KBM is near marginal stability. A self-consistent beta scan, based on a Miller model MHD equilibrium, indicates that the critical beta is 11% for strongly growing kinetic ballooning modes. The toroidal mode numbers and the real frequency are of the order of those expected for the KBM, with the growth rates peaking when the mode number is in the range 6 to 9.

Initial gyrokinetic calculations of this NSTX L-mode at an earlier time [11] show that for r/a = 0.35 the microtearing is maximum at 0.3 $k_\perp\rho_s$. At r/a = 0.45 the maximum ITG growth rate occurs at 0.3 $k_\perp\rho_s$ and ETG peaks at 20 $k_\perp\rho_s$. At r/a = 0.65, ITG is most strongly growing at 0.7 $k_\perp\rho_s$ and ETG is maximum at 30 $k_\perp\rho_s$. Other modes are not found to be unstable.

The effect of temperature gradients and magnetic shear variations on microstability was also studied at r/a=0.35 with fully electromagnetic calculations following four plasma species and including the complete electron response. In this case however, analytic Miller-type equilibria were used, rather than numerical equilibria. At this radius the local β is 19%. The calculations lead to microtearing modes and ITG/TEM modes, in addition to other

electromagnetic modes of longer wavelength and even parity, which rotate in the ion diamagnetic direction (possibly kink modes). Core microtearing modes have been found unstable in every NSTX plasma examined, unless the plasma has reversed shear or is assumed collisionless [12, 13]. Figures 3-4 show the effects of a scan of both magnetic shear and temperature scale length variations on the ITG/TEM and microtearing long wavelength modes. As expected, microtearing is destabilized for positive temperature gradients and low magnetic shear (Fig. 3) while ITG is destabilized by reversed temperature gradients and low magnetic shear (Fig. 4). A more complex mixing length model than applied to the C-Mod case will be needed for NSTX, to properly include all the long wavelength modes.

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Table I. Comparison of linear ITG mixing length model transport coefficients to anomalous transport coefficients derived from transport analysis of experiment

r/a	0.25	0.45	0.65
$\chi_{mix} = \gamma/\langle k_\perp^2 \rangle$ (m^2/s)	0	0.76	1.04
χ_{eff}-$\chi_i^{Chang\text{-}Hinton}$ (m^2/s)	0	0.4	0.8

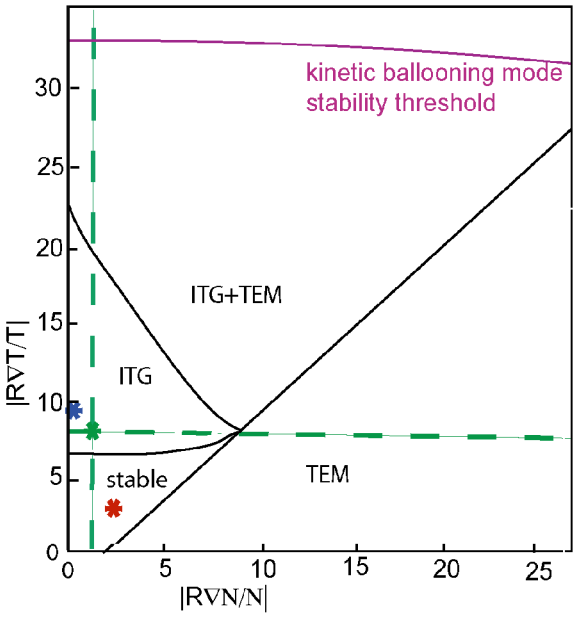

Fig. 1. Phase diagram for linear instability of ITG and TEM drift modes for the C-Mod plasma before ITB formation. Diagram adapted from Fig. 1 of Ref. 10. Star symbols indicate three C-Mod radial locations simulated, with stable conditions found in the plasma core (red), weakly unstable ITG at the barrier region (green) and strongly unstable ITG outside the barrier region (blue). Dashed lines map locations for linear simulations carried out for variations of the barrier region.

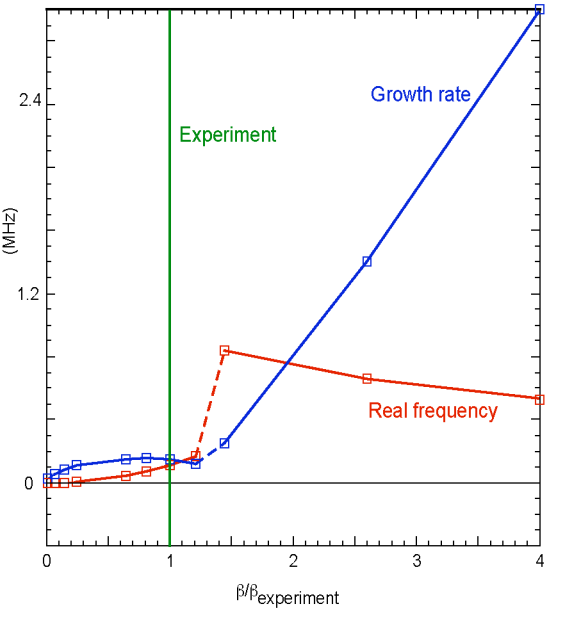

Fig. 2 Growth rates and real frequencies of fastest growing mode in NSTX shot 112996 at 0.4 sec, r/a=0.55 A beta scan shows that the experiment is dominated by ITG/TEM and is just below the critical threshold for the kinetic ballooning mode. The KBM may be limiting beta at this radius, β_crit ~11%.

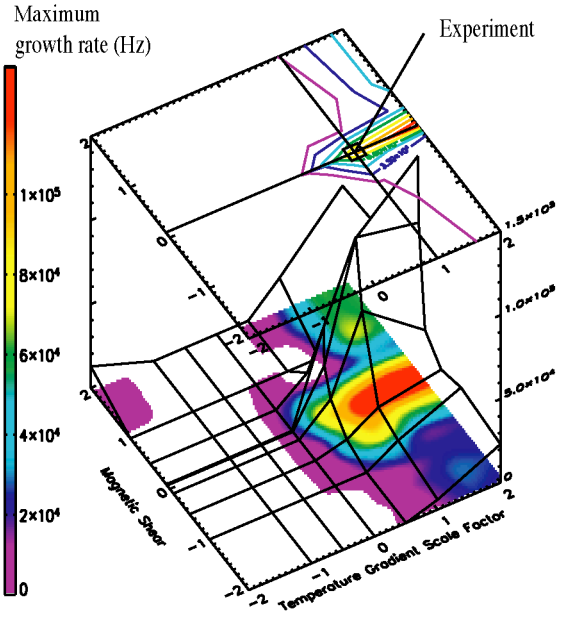

Fig. 3 Growth rates for microtearing mode identified in calculations of NSTX L-mode plasmas with variations in magnetic shear and scaled temperature gradients of all four species. Mode is destabilized at low magnetic shear and positive temperature gradients.

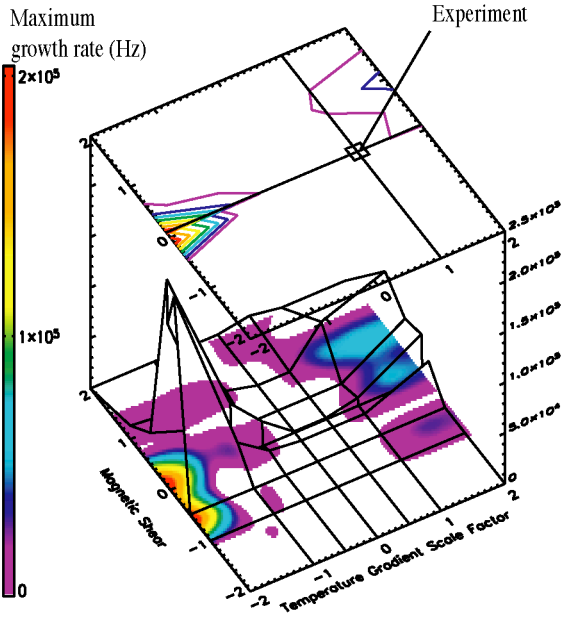

Fig. 4 Growth rates for ion temperature gradient modes identified in calculations of NSTX L-mode plasmas for variations in magnetic shear and scaled temperature gradients of all four species. Mode is destabilized at low magnetic shear for increased temperature gradients of positive and negative sign.

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