Nonlinear Turbulence Simulations for NSTX H-modes

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Present evidence points to remarkably resilient electron temperature profiles in high density H-mode plasmas on NSTX [1], suggesting that the underlying electron thermal transport mechanisms respond in a highly nonlinear fashion to changes in the gradients. This paper uses measured plasma profiles (Fig. 1) as input to linear gyroknetic analysis to identify candidate microinstabilities that may be responsible for the electron thermal transport. The criteria for useful nonlinear microstability analyses are discussed along with necessary approximations and computational issues.

These studies have been performed with the massively parallel code GS2 [2]. The linear simulations are fully electromagnetic, follow electron as well as three ion species and include the complete electron response. Initial linear simulations were based on a model calculation of the current profile with central reversed shear, leading to no unstable linear drift modes in the plasma core. However, recent magnetic diffusion modeling indicates that the plasma *q* profile may not be reversed. Unstable microtearing modes are found in the plasma core at *r/a*=0.25, in the ion temperature gradient/trapped electron mode (ITG/TEM) range of wavevectors with γ^{lin}~0.02MHz (Fig. 2). Near the midradius, at *r/a*=0.65, the strongest modes are also microtearing modes as found previously [3]. ***ExB*** shearing appears sufficient to stabilize ITG/TEM modes near the edge, at *r/a*=0.80, where the ETG mode is also linearly unstable, γ^{lin}~1.0MHz [3].

Initial nonlinear simulations examine the case at *r/a* =0.25 because low values of magnetic shear there limit the number of wavevectors and computational time required. The case at *r/a* =0.65 is also of interest, as presently the *q* profile, and the magnetic shear are more reliably known at this location. Many linear gyrokinetic calculations were needed to determine the computational domain appropriate to treat the extended microtearing modes, which are coupled in the twisted flux-tube geometry.

Nonlinear microtearing simulations are complicated, compared to ITG mode simulations, by several new effects. First, three fields (electrostatic potential, parallel and perpendicular magnetic fields) rather than one must be included in the calculation. Second, the eigenfunction extent along the field line is longer than the typical ITG electrostatic eigenfunction, requiring five 2π periods at r/a =0.65 and seventeen 2π periods along the field line at r/a =0.25 to resolve all three field eigenfunctions. And finally this plasma exhibits a broad spectrum of weak, well converged unstable modes with tearing parity. These extend from $k_\theta\rho_s$=0.1 to 0.8 at r/a =0.25 at 0.6 sec and from $k_\theta\rho_s$= 0.1 to 1.0 at r/a =0.65 at both 0.4 sec and 0.6 sec (Fig. 3). Well converged, unstable modes with odd and even parity are found at higher wavevectors, up to $k_\theta\rho_s$<2–3 at r/a =0.65 at 0.4 sec and 0.6 sec. At the earlier time, 0.4 sec, the modes, aside from $k_\theta\rho_s$=0.1, do not have tearing parity and the unstable mode growth rates at r/a =0.25 are smaller, γ^{lin}~0.003MHz. Connor, *et al.* [4] have analytically examined the conditions for linear instability of the microtearing mode in the intermediate collisionality regime (for a large aspect ratio tokamak). For $\nu_e, \nu_i =$, instability occurs only if $\partial_r T_i > \partial_r T_e$. This condition is satisfied at the core radii in Fig. 1 except for r/a =0.25 at 0.4 sec. It is consistent with the stability analysis just described, though NSTX is low aspect ratio.

These considerations mean that nonlinear microtearing calculations require one to two orders of magnitude more cpu time and memory than typical nonlinear ITG mode simulations. Nonlinear calculations are therefore being pursued with ions and electrons only, and no impurities. The linear simulations originally included four species: electrons, deuterium ions, carbon impurities and high energy beam ions. Reduction of species to electrons and ions only at r/a=0.65 made little change in γ^{lin} other than a reduction by 10% at $k_\theta\rho$=0.6. The spectrum of converged, tearing parity, instabilities was unchanged at r/a=0.65 at 0.6 sec. The spectrum extent was reduced to $k_\theta\rho_s$ = 0.2 to 3 for 0.25 r/a at 0.6 sec and to 0.1 to 1 for r/a=0.65 at 0.4 sec. Computational time required for ITG range computation was reduced to 16 sec from 37 sec. Similar changes with reduced species were found at r/a=0.25.

Nonlinear simulations are being carried out on the NERSC IBM SP supercomputer, which has the required large memory capacity. With 336 processors on 42 nodes with 8 processors per node, each processor has up to 4 GB of memory. The computational domain has 758 million meshpoints in a rectangular box (at the outside plasma midplane) with 15 ρ_s in the x direction and 63 ρ_s in the y direction. The nonlinear terms are evaluated on a grid with 243 points in x and 27 points in y, for 9 k_y modes greater or equal to zero, and 161 k_x

modes, after dealiasing. In terms of input variables to the nonlinear GS2 code, the rule for determining the number of k_x modes has been generalized: $N_x \approx N_y \cdot (nperiod\text{-}1) \cdot (2\pi\, rq'/q) \cdot L_x/L_y$ when more than one field period is needed to represent the necessary connections for the eigenfunctions. Here N_x is defined to be the integer part of the quantity $(n_x\text{-}1)/3$, n_x being the number of positive k_x modes. Also, $nperiod = (1+N_p)/2$, where N_p is the number of 2π field periods and L_x and L_y are the box dimensions.

What is the width of the NSTX microtearing mode? Simple reasoning leads to very large radial widths for the $\delta B_\parallel$ component of this mode at r/a=0.25. From Figs. 2 and 3, we can estimate $<k_x>=<k_y>\cdot (rq'/q)\cdot \Delta\theta$. With $<k_y> = 0.5/\rho_s$, $(rq'/q) = 0.15$ and $\Delta\theta = 1.2$ radians, the radial width is $\Delta x=2\pi/<k_x>=84\rho_s \sim 84\rho_i$. Near the core, $\rho_i = 0.017$ m, so that the radial width of the tearing mode ~1.4 m, greater than twice the plasma midplane minor radius, $2a_{mid}$=1.2 m. More detailed calculations are needed to properly answer this question.

Table I shows a comparison at 0.4 sec and 0.6 sec for three radii of the experimentally determined ion and electron thermal diffusivities and the linear microstability analysis of long and short wavelength drift modes. Initial conclusions are that low ion diffusivities may be a consequence of stabilized ion temperature gradient modes and that high electron diffusivities may be due to ETG in the outer regions of the plasma and to electron temperature gradient driven, microtearing modes in the plasma core. Nonlinear simulations are in progress for quantitative comparison and benchmarking the model to experiment.

*Supported by USDoE contract No. DE-AC02-76CH03073

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Table I. Comparison of observed transport coefficients to linear microstability analysis.

t=0.4/0.6s	χ_i	χ_e	ITG, μtearing	ETG
r/a=0.25	$< \chi^{neo}$	>> χ_i	Stable ITG, unstable μtearing	stable
r/a=0.65	$< \chi^{neo}$	>> χ_i	Likely stable ITG, unstable μtearing ExB effect unknown on μtearing	unstable/ stable
r/a=0.80	$< \chi^{neo}$	>>	likely stable ITG	unstable

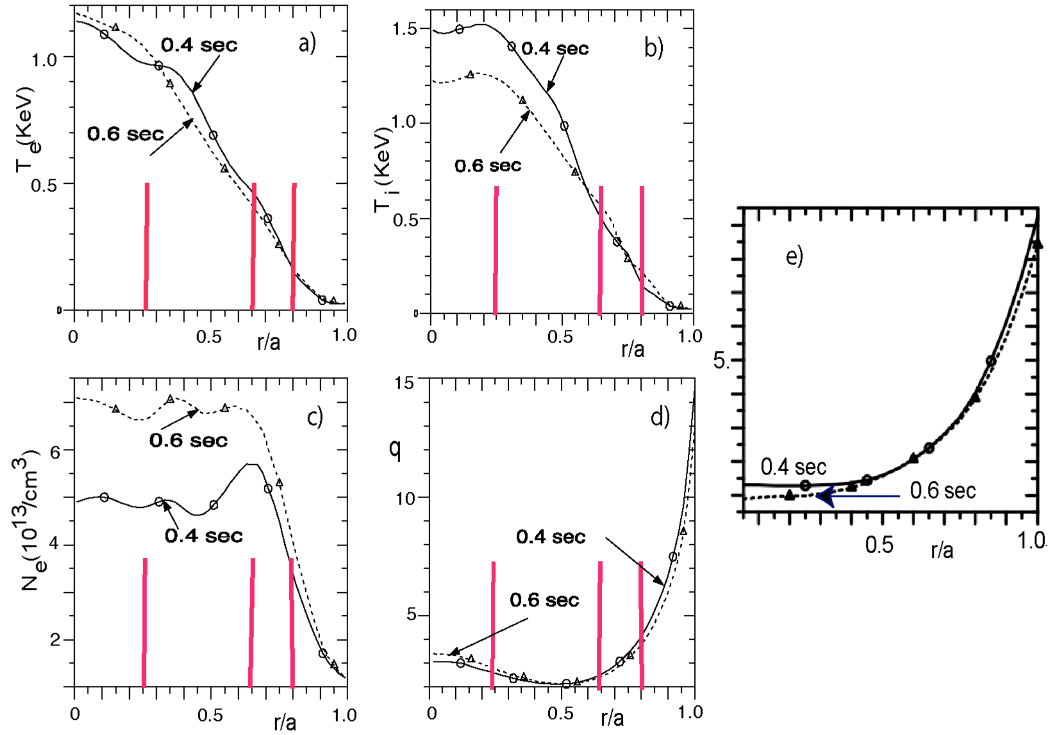

Fig. 1. Profiles from high density H-mode at 0.4 and 0.6 seconds. a) plasma electron temperature, b) ion temperature, c) electron density, d) EFIT derived q profile, e) q profile from magnetic diffusion.

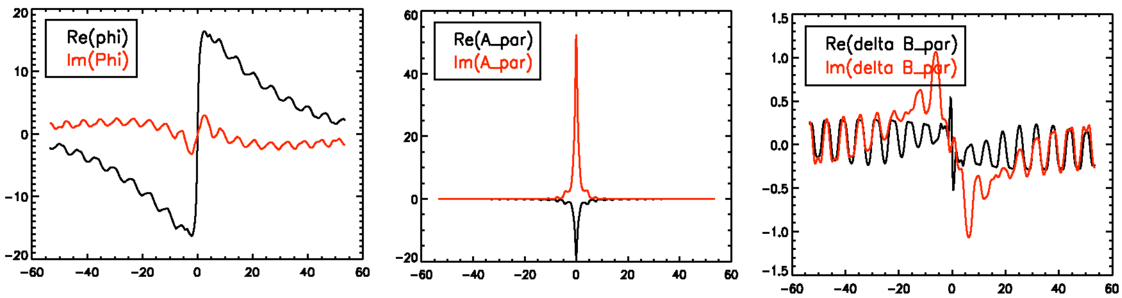

Fig. 2 Real and imagninary components of electrostatic potential and magnetic field eigenfunctions for NSTX H-mode plasma at r/a=0.25 and 0.6 sec. Microtearing mode shows tearing parity in $A_{//}$ component. Mode eigenfunctions shown for seventeen 2π field period linear simulations and $k_\perp \rho_s$=0.5.

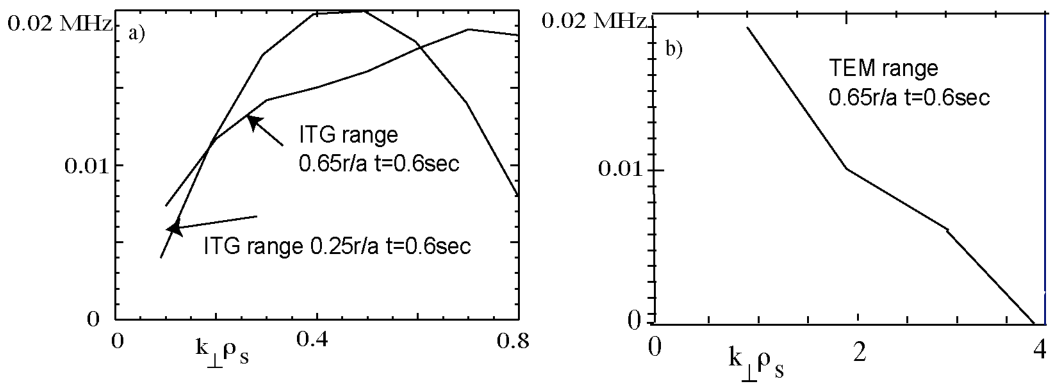

Fig. 3 Growth rate spectra for microtearing modes in NSTX H-mode at r/a=0.25 and 0.65 for 0.6 sec in the a) ITG and b) TEM wave vector ranges.