Nonlinear Gyrokinetic Simulations of Ion Turbulence in Impurity Seeded and High Density Toroidal Plasmas

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Abstract
Ion temperature gradient-driven (ITG) turbulence plays an important role in explaining measured ion thermal transport in tokamaks, particularly under L-mode conditions. Nonlinear global toroidal gyrokinetic simulation results are presented with radiative impurity seeding in TEXTOR-like L-mode plasma. Reduced levels of ITG turbulence and ion heat transport are observed, possibly explaining the origin of the improved confinement regime radiative improved(RI)-mode. In a separate investigation, ITG turbulence in several DIII-D-like discharges has been analyzed using our nonlinear model under different experimental conditions, with high and low density and central ion temperature, and comparisons with experiment have been favorable. Turbulence radial correlation lengths have been compared and are found to be similar when the effect of zonal flows is included.

1. Nonlinear Gyrokinetic Simulation of Ion Thermal Transport in Impurity-Seeded Plasmas

A novel improved confinement regime, called the Radiative Improved(RI)-mode has been achieved in target L-mode plasmas in tokamaks such as TEXTOR-94[1] and DIII-D[2], using neon injection. Recently it has been shown experimentally that turbulent fluctuations are suppressed in the edge region[3] as well as deeper into the core[2]. A possible model to explain the observed change in global energy confinement behavior from L-mode to RI-mode is the suppression of the ion temperature gradient-driven(ITG) instability which is believed to be a dominant feature in L-mode tokamak plasmas. The linear theory does not give a complete description of turbulent transport due to the complex dynamics of ITG instabilities, which involves energy transfer among different toroidal mode helicities, radial propagation, and turbulence-driven zonal flows, all occurring during the saturation and quasi-steady phases of temporal evolution[4]. We therefore use the results of nonlinear gyrokinetic simulations to obtain local transport coefficients and fluctuation spectra. The plasma density, temperature and magnetic field profiles are obtained from TEXTOR-94 experiments under L-mode and RI-mode phases of the discharge.

The simulation results indicate a suppression of the turbulence and corresponding reduction in the anomalous ion thermal transport with neon concentrations between 1-3 per cent using the L-mode profiles initially. This is shown in *FIG. 1* for the L-mode profile case with and without neon.

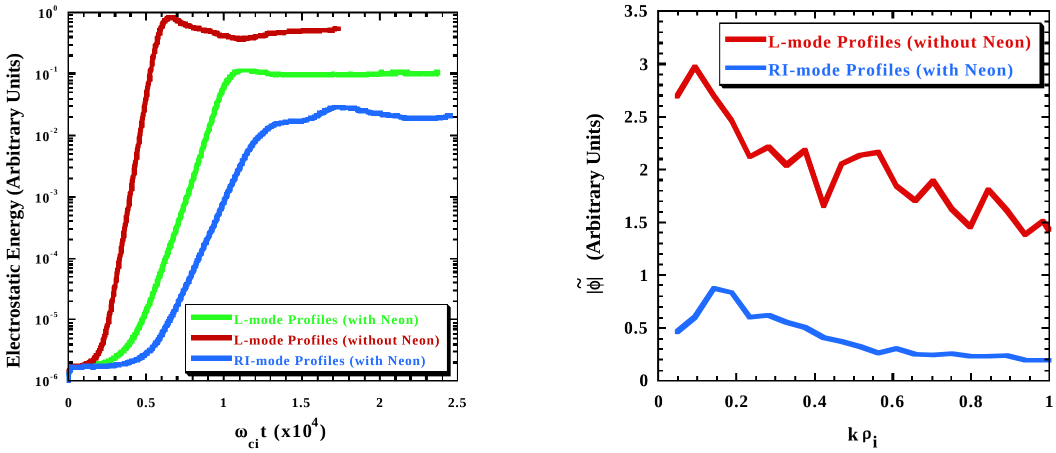

FIG. 1 Time evolution of the volume averaged electrostatic energies and saturated electrostatic potential amplitudes versus wavenumber using L-mode profiles with and without neon and RI-mode profiles with neon.

The main stabilization mechanism arises from the combined effects of dilution, modified ion polarization drift effects and curvature and gradient-B drift resonances from the impurity species. These can eventually reduce the linear growth rates and turbulence decorrelation rate to a level comparable with the **ExB** shearing rate, depending on the concentration and impurity distribution. Simulations using the RI-mode profiles, also displayed in *FIG. 1* and taken shortly after the transition, show a further reduction in anomalous ion thermal transport due to the combined effects of ion gradient scale length change and density profile peaking. *FIG. 1* also illustrates the saturated electrostatic potential amplitude versus wavenumber for both L-mode and RI-mode profile cases indicating turbulence reduction in the spectral range $k\rho_i$=0.03-1. The drop in the fluctuation level and saturated spectra lead to a reduction in the anomalous ion transport by a factor of 2-3 which is comparable to the experimental improvements in the ion channel. Finally, we have also observed an inward flux of the main background ion species with a corresponding outward flux of neon during the evolution of the turbulence. This leads to reduced neon accumulation in the core region of the plasma.

2. Nonlinear Gyrokinetic Analysis of Ion Temperature Gradient Driven Turbulence in DIII-D-Like Discharges

We are continuing to analyze ITG turbulence in DIII-D-like discharges under various experimental conditions using nonlinear toroidal gyrokinetic particle-in-cell calculations [5]. These calculations are electrostatic with adiabatic electrons but include zonal flows generated by the fluctuations themselves through Reynolds' stress. In particular, we have proceeded to analyze DIII-D shots 99805 (high line average density) and 99807 (lower line average density) which were designed for the purpose of characterizing ITG under different experimental conditions [6]. For these discharges, the plasma cross-section was nearly circular to minimize flow effects and they are therefore particularly well suited for analysis with our circular cross-section gyrokinetic code. However, because these discharges have low central ion temperatures (1 keV), the calculations cover many hundreds of ion Larmor radii per minor radius. Mostly because of limitations on computer memory, we have in fact been restricted to calculations which cover only 60% of the experimental plasma cross section. Fits to the experimental q profiles and profiles of the ratio of density gradient scale length to temperature gradient scale length $\eta_i=L_n/L_T$ are displayed in *FIG. 2* as a function of radius r_{sim} in the calculations normalized to the minor radius a. It is clear that η_i is much larger for 0.2 r/a 0.6 for shot 99805 as compared to shot 99807 where η_i hovers around the linear slab threshold.

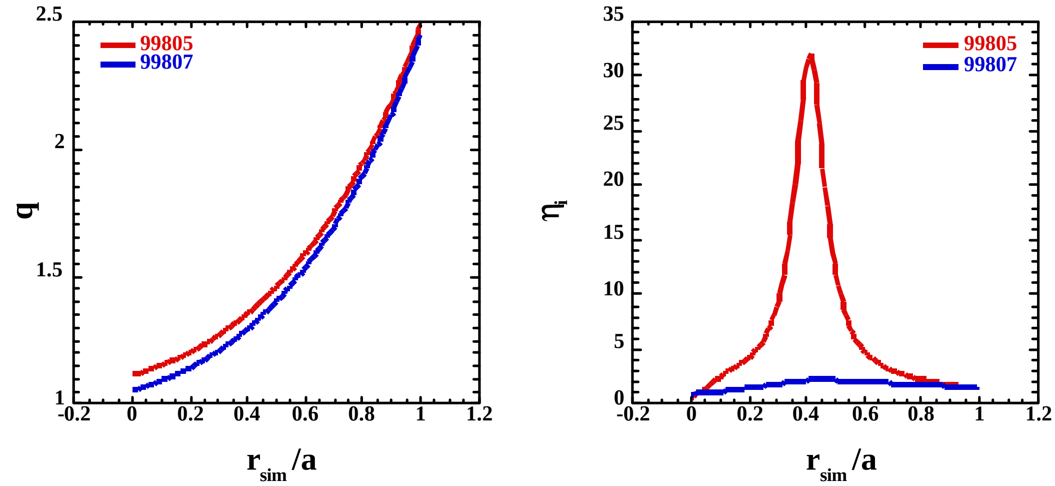

FIG. 2 Radial profiles of q and η_i in the calculations.

Results from these calculations are shown in *FIG. 3* where volume averaged fluctuations levels and heat fluxes are displayed as a function of time normalized to the ion cyclotron frequency ω_{ci}.

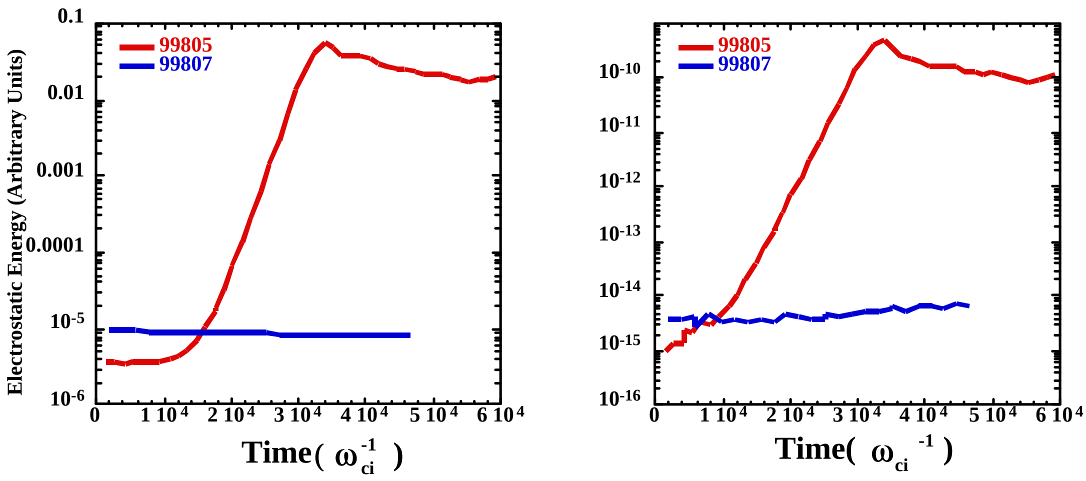

FIG. 3 Time evolution of volume averaged electrostatic energies and energy fluxes for low (shot 99807) and high (shot 99805) values of η_i.

It is apparent from *FIG. 3* that nothing grows out of noise for the low η_i discharge (shot 99807) while well developed linear growth and saturated phases are evident in the time evolution of the electrostatic energies and heat fluxes displayed for the high η_i discharge (shot

99805). Experimentally, increased fluctuations concentrated over low frequencies are observed coincident with the onset of confinement saturation. These experimental features and the gyrokinetic calculations suggest that ITG may be the dominant mode in these experiments.

Another discharge with much higher central ion temperature (~16 keV) was also analyzed for ITG activity using nonlinear gyrokinetic calculations. Details about profiles and parameters can be found in Ref. [5] and Rhodes et al. [7]. Suffice it to say that the calculations accommodate the experimental number of ion Larmor radii and cover the full extent of the experimental minor radius because of the higher central ion temperature. Their other salient feature is that an equivalent data analysis technique to determine radial correlation lengths was used in the experiment and in the calculations. The result of this analysis is shown in *FIG. 4* where radial correlation lengths as a function of minor radius are displayed. The calculated radial correlation lengths are commensurate to the experimentally measured ones and both correspond to several times the local ion Larmor radius. When zonal flows are excluded from the simulations, the calculated radial correlation lengths are about one order of magnitude larger [7].

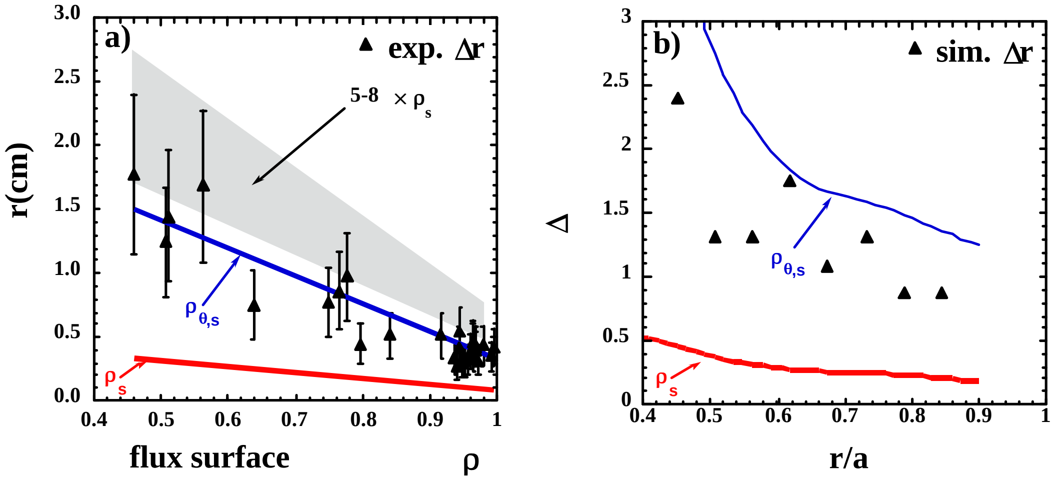

FIG. 4 Radial profile of the radial correlation lengths in the experiment (a) and in the simulations (b).

3. Summary

The results described herein demonstrate that it is possible to carry out gyrokinetic calculations with a sufficient degree of realism such that meaningful comparisons can be made with experimental data. Emerging massively parallel computers are enabling inclusion of electron physics and electromagnetic effects in larger scale calculations which will facilitate ever more detailed comparisons between experiments and simulation.

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Acknowledgments

This work is part of the Plasma Science Advanced Computing Initiative (PSACI) Microturbulence Project supported by the USDOE Office of Fusion Energy Sciences under grant DE-FG03-86ER53225. It is also supported by the Natural Sciences and Engineering Research Council (NSERC), Canada. Computational resource support provided by the USDOE National Energy Research Scientific Computing Center (NERSC) on the massively parallel Cray T3E and IBM SP3 platforms and the Cray T3E at the Central Institute of Applied Mathematics(ZAM), Forschungszentrum Juelich, Germany is gratefully acknowledged.