31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-2.185 (2004)

Transport from Overlapping Electron and Ion Driftwave Instabilities

G.M. Staebler[1] , J.E. Kinsey[2], and R.E. Waltz[1]

[1]*General Atomics,P.O. Box 85608, San Diego, California 92186-5608*
[2]*Lehigh University, Bethlehem, Pennsylvania*

The electron temperature gradient (ETG) mode is a likely contributor to electron thermal transport in tokamaks. The ETG modes are dominantly unstable for poloidal wavelengths shorter than the ion gyroradius (high-k) where the ion response is abiabatic. Thus, they do not directly produce ion thermal or momentum transport or particle transport. Two potential mechanisms whereby ETG modes could produce transport in these channels are explored in this paper: a nonlinear coupling between high-k ETG modes and ions at low-k and a direct coupling when ETG modes and ion temperature gradient (ITG) modes are unstable in overlapping wavenumber ranges. It will be shown that the particle and momentum transport required to match experiment is small compared to the ETG driven electron thermal transport. Even quasilinearly ETG modes can produce ion transport if the ITG and ETG modes are both unstable at low-k. The implications of this for transport will be explored at the quasilinear level. A new gyro-Landau-fluid (GLF) closure model has been constructed in order to build a transport model which can include the coupling between electron and ion modes including trapped particles. The first growth rate spectra from this model will be shown to give an accurate approximation to the kinetic linear growth rates of drift-ballooning modes in tokamaks.

I. Transport Within a Transport Barrier

There is a body of significant evidence that ETG modes provide the required level of electron thermal transport within a transport barrier. Within a transport barrier region, where the ITG and trapped electron modes (TEM) are predicted to be suppressed by $E\times B$ velocity shear, the ion thermal transport is consistent with neoclassical levels [1,2]. The theory based transport model GLF23 [1] computes the ETG driven electron thermal transport from a quasilinear model with a mixing length estimate for the fluctuation amplitude. The GLF23 predicted electron temperature profiles within a transport barrier agree well with experiment [1,2]. Within the barrier region the GLF23 model has only neoclassical ion thermal transport and ETG mode driven electron thermal transport. The electron temperature profile is not very sensitive to the amplitude of the saturated turbulence but does depend strongly on the critical electron temperature gradient for the ETG modes to become unstable. Exact gyro-kinetic calculations of this critical gradient have shown that the electron temperature profile at its steepest region in the core of the plasma follows the ETG threshold gradient [3-5]. Strongly negative magnetic shear increases the ETG threshold gradient and the electron profile is found to also steepen maintaining a marginally unstable condition. Even with strong electron cyclotron heating during the plasma current ramp, which produces very steep electron temperature profiles, the profile tracks the calculated ETG critical gradient [6]. Even for discharges without a transport barrier, the electron temperature profile is at the ETG mode critical gradient over much of the plasma cross section [7]. In the marginally stable zone the driftwave spectrum looks like that of Fig. 1(a) which is taken at r/a = 0.4 in an L-mode DIII-D discharge (105663) [7]. Since the ETG and ITG modes do not overlap there is very little particle and ion energy flux (or momentum transport) driven quasilinearly by the ETG modes. The quasilinear weights (flux divided by fluctuation amplitude squared) for the ion and electron energy flux and the particle flux are shown in Fig. 1(b). This type of spectrum with a stable gap between ETG and ITG/TEM modes is assumed in GLF23. Hence, there is no ETG driven particle or ion momentum transport in GLF23. The predicted electron density profile for DIII-D discharge 98549 at 1.5 s is shown in Fig. 2. This is an Elmy H-mode with a negative central magnetic shear and an internal barrier extending from the center to r/a = 0.32 [2]. The predicted density profile is much more peaked than the measured one for the GLF23 case (dashed). The temperatures were not evolved for the dashed case. Only neoclassical particle transport (without the Ware pinch) is used in the barrier region for the dashed case. It is possible that ETG modes can drive particle transport nonlinearly. It is expected that the ETG modes will have a cascade of fluctuation energy down to long wavelengths. If this cascade reaches below the ion gyroradius wavelength then a non-adiabatic ion response can be excited and hence some level of particle transport. The $E \times B$ nonlinearity will produce a three wave coupling between two ETG modes and an ITG mode if the ETG wavenumbers differ by the ITG wavenumber. The strength of this three wave coupling will scale with the amplitude of the ETG fluctuations and hence should be related to the level of electron thermal transport driven by the ETG modes. The size of the particle transport caused by ETG modes which is needed to obtain agreement with experiment can be estimated by adding an ad-hoc particle diffussivity which is a fraction of the ETG electron thermal dif-

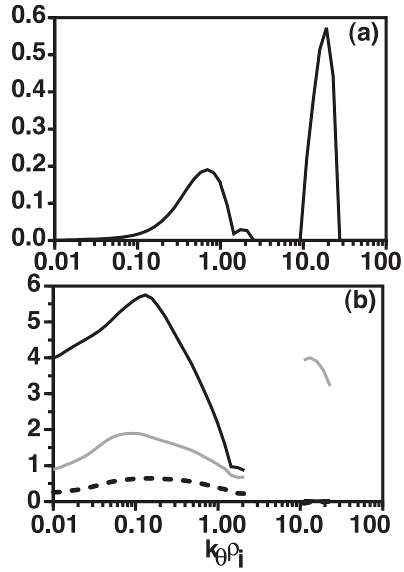

Fig. 1. (a) Spectrum of drift wave growth rates normalized to c_s/a at r/a = 0.4 for DIII-D discharge 105663. (b) Quasilinear weight spectrum for ion energy flux (black), electron energy flux (grey) and particle flux (chain).

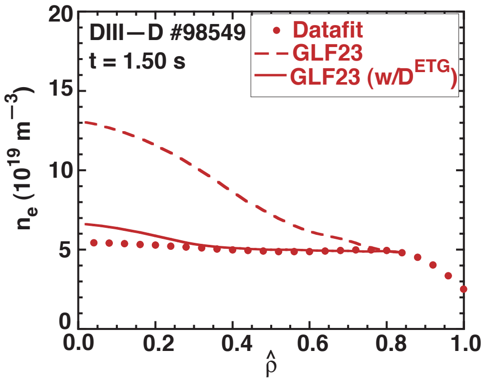

Fig. 2. GLF23 Predicted electron density with ad-hoc particle diffusivity equal to 15% of ETG thermal diffusivity (solid) and without this enhancement (dashed) compared to fit through measured data.

fussivity to the GLF23 model. Agreement is reached with a fraction of 15% as shown in Fig. 3 (solid).The temperatures were also evolved for this case obtaining good agreement [2]. Similarly, agreement with the ion toroidal rotation profile can be achieved if a toroidal momentum diffussivity which is 25% of the ETG electron thermal diffussivity is added to GLF23. These estimates are small enough that this nonlinear mechanism may be sufficient. This motivates pursuing a more quantitative test with a quasilinear evaluation of the three wave coupling and the resulting transport in the future. It may also be possible to explore this coupling with a simplified 2-D nonlinear turbulence simulation using the new GLF model.

In the outer region of the plasma the drift wave spectrum has a strong overlap between ITG and ETG modes. In Fig. 3(a) the gyrokinetic calculation of the spectrum for the discharge 105663 of Fig. 1 is shown at r/a = 0.8. There is a continuous spectrum of electron drift frequency instabilities all the way from the high-k ETG peak into the low-k range. The electron modes get a substantial boost from the trapped electrons at the low-k end but there is no discontinuity in the frequency. The quasilinear weights for ion and electron energy flux and particle flux are shown in Fig. 3(b). For $k_\theta \rho_i < 1$ there is significant particle and ion energy flux driven by the electron modes. Note that the electron energy flux always has the largest weight unlike the ITG modes in Fig. 1(b) which favored ion energy flux. The impact of this overlap on net transport and plasma profiles is hard to estimate. It is important to be able to extend the GLF23 transport modeling out to the separatrix in order to be able to model the H-mode transport barrier and the pedestal region. It is difficult to extend the GLF23 modeling even to the top of the pedestal in H-modes (r/a > 0.8) because the ITG/TEM growth rates are often too small and an $E \times B$ shear induced transport barrier forms at a radius which contradicts experiment. It is anticipated that if the GLF23 model could include the overlapping of ETG and ITG modes that this situation would improve.

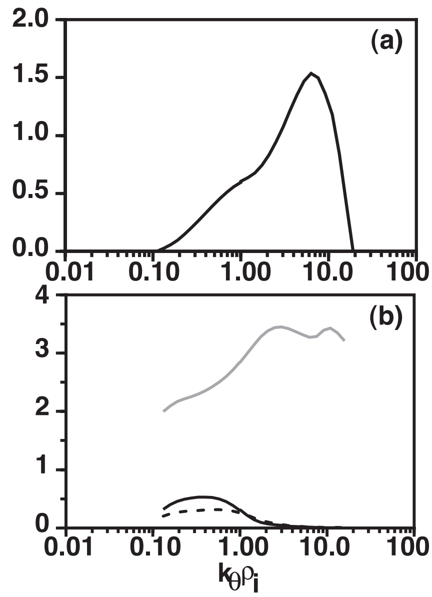

Fig. 3. (a) Spectrum of drift wave growth rates (c_s/a units) at r/a = 0.8 for DIII-D discharge 105663. (b) Quasilinear weight spectrum for ion energy flux (black), electron energy flux (grey) and particle flux (chain).

Gyro-Landau-fluid models have been shown to give an accurate approximation to the kinetic linear growth rates of drift-ballooning modes in tokamaks [8-10]. Even though the GLF model GLF23 has ETG modes, they are assumed to be decoupled from the ions. A new set of GLF equations is needed in order to treat coupling between ETG modes and ions. The new model [11] has three moments for trapped particles and twelve moments for passing particles. The closure of the highest moments yields coefficients which are functions of the trapped particle fraction. These coefficients are fit by minimizing the error between the GLF response functions and the exact kinetic result. A model for the boundary between those trapped particles which can bounce average a given wave and those which can have a Landau resonance with the wave has been developed. The final system of GLF equations for ions and electrons is valid from the lowest frequency trapped ion modes all the way up to the highest frequency ETG modes. The GLF model gives a faster calculation of the linear eigenmodes than a gyrokinetic initial value code. The first results from the new GLF equations is shown in Fig. 4. The growth rate spectrum for modes with a frequency in the ion and electron drift directions are shown separately. Only the most unstable mode for each sign of the frequency is plotted. The GLF growth rates compare very well with the gyrokinetic growth rates from an initial value code [12]. The initial value code can only find the most unstable mode regardless of the sign of the frequency. The GLF eigenmode code reveals that there is a wide region of overlapping ion and electron modes which cannot be found with an initial value code. The new GLF model has applications as an analysis tool for experimental discharges (both growth rates and critical gradients) and as the eigenmode solver in a quasilinear transport model similar to GLF23 and for non-linear GLF simulations of coupled ETG+ITG/TEM modes.

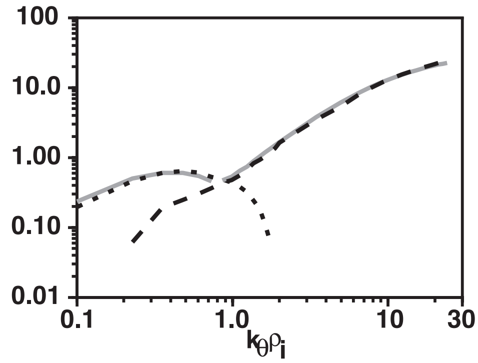

Fig.4 . Growth rate spectrum (c_s/a units) for (a/L_T=6, a/L_n=1, s=1, α=0, T_i/T_e=1, R/a=3, r/a = 0.5, electrostatic) comparing the gyrokinetic initial value code [12] (grey) with the new GLF eigenvalue code [11]. The GLF code resolves the electron (dashed) and ion (chain) frequency branches. The maximum growth rate and crossover point agree very well between the two codes.

This work was supported by the U.S. Department of Energy under DE-FG03-95ER54309 and DE-FG02-92ER54141.

[1] R.E. Waltz, *et al.,* Phys. Plasmas **4**, 2482 (1997).
[2] J.E. Kinsey, G.M. Staebler and R.E. Waltz, Phys. Plasmas **9**, 1676 (2002).
[3] B.W. Stallard, *et al.,* Phys. Plasmas **6**, 1978 (1999).
[4] C.M. Greenfield, *et al.,* Nucl. Fusion **39**, 1723 (1999).
[5] G.M. Staebler, *et al.,* Proc. 17th IAEA Fusion Energy Conf., Yokohama, Japan (1998).
[6] C.M. Greenfield, *et al.,* Proc. 27th Euro. Conf. on Control. Fusion and Plasma Phys., Budapest, Hungary, Vol. **24B** (Euro. Phys. Soc., 2000) P544.
[7] J.C. DeBoo, *et al.,* Proc. 29th Euro. Conf. on Plasma Phys. and Control. Fusion, Montreux, France, Vol. **26B** (Euro. Phys. Soc., 2002) P-2.064.
[8] G.W. Hammett and F.W. Perkins, Phys. Rev. Lett. **64**, 3019 (1990).
[9] R.E. Waltz, R.R. Dominguez, and G.W. Hammett, Phys. Fluids **B4**, 3138 (1992).
[10] M.A. Beer and G.W. Hammett, Phys. Plasmas **3**, 4018 (1996).
[11] G.M. Staebler, *et al.,* to be submitted to Phys. Plasmas.
[12] M. Kotschenreuther, *et al.,* Comp. Phys. Comm. **88**, 128 (1995).