29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, P-5.046 (2002)

Electron Temperature Gradient Model as Part of Integrated Predictive Modeling

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Introduction

A strong electron temperature gradient together with nonadiabatic trapped electron response may cause an instability called the Electron-Temperature-Gradient (ETG) mode that produces enhanced electron transport. Recent gyro-kinetic numerical simulations [1] indicate that the electron heat flux driven by this turbulence is significantly underpredicted by simple mixing length estimates in certain parameter regimes, and ETG streamers can result in significantly larger electron heat fluxes. Renormalization of the GLF23 transport model [2] indicates that the ETG contribution to electron thermal transport is much larger than was considered before.

Several theory-based ETG models are studied in this report. Particular attention is focused on a fluid model with electromagnetic effects [3, 4] and a model derived from the numerical solution of the linear gyrokinetic equations [1]. A new ETG transport model is developed for use in integrated predictive modeling codes and is applied to H-mode discharges with internal transport barriers (ITBs) in DIII-D and JET.

Models for ETG turbulence transport

The electron thermal transport driven by the ETG turbulence has been studied much less than the transport driven by the ITG and TEM turbulence. In a linear, electrostatic, and adiabatic limit, the mixing length estimate indicates that electron transport caused by the ETG modes is much smaller than the transport caused by the ITG modes. The basic equations that describe the electrostatic ETG and ITG instabilities are the same, and these modes are isomorphic in this limit. For typical fusion plasma conditions, the simple mixing length estimate yields $\chi_i \propto 60\chi_e$ [1]. It was believed that the transport is controlled by the modes with the longest wavelength, such as the ITG and TEM modes. However, even in the linear limit, there are a number of effects that reflect important differences between ion and electron scale physics. For example, electromagnetic effects might play a more important role for the electron thermal transport than for the ion thermal transport. Nonadiabatic effects and effects of Debye shielding are expected to be more important as well [1, 5]. At the same time, the stabilizing effect of Debye shielding becomes tangible only if the electron Debye length λ_{De} exceeds the electron gyroradius ρ_e, while in the general case $\lambda_{De}/\rho_e \propto B_T/n_{e19}^{1/2} \leq 1$. The effect of nonadiabatic ion response is studied in Ref. [5] and is found to be rather small (see, for example, Fig. 3 in Ref. [5]).

A hydrodynamic theory of short wavelength ETG turbulence, which includes electromagnetic effects, has been developed in Ref. [3]. As a generalization of this study, a simple analytical expression for the electron thermal diffusivity driven by the ETG modes was constructed in Ref. [4]:

$$\chi_e^{(0)} = \begin{cases} C_e^{es} q^2 \left(\dfrac{R}{L_{Te}}\right)^{3/2} \left(\dfrac{c\rho_e}{eB_T}\right)\left[\nabla T_e - C_L\left(\dfrac{|\hat{s}|T_e}{qR}\right)\left(1+\dfrac{T_e}{T_i}\right)\right], & l_{c,e}^{es} \geq \delta_e \\ C_e^{em} q^{\nu} \dfrac{c^2}{\omega_{pe}^2}\dfrac{\upsilon_e}{(L_{Te}R)^{1/2}}, & l_{c,e}^{es} < \delta_e \end{cases}, \tag{1}$$

where q is the safety factor, $\hat{s}$ is magnetic shear, δ_e is the collisionless skin depth, $l_{c,e}^{es} = q\rho_e R/L_{Te}$ is the electron mixing length, $L_{Tj} = -(d\ln T_j/dr)^{-1}$, $C_e^{es} = C_e^{em} = 0.06$, $C_L = 1.88$, and $\nu \approx 0$ are semi-empirical parameters. The two limits in Eq (1) are manifestations of the fact that the electron thermal diffusivity is electromagnetic, if the electron mixing length is less than the collisionless skin depth, and electrostatic otherwise. While Eq (1) was derived for turbulence far from the instability threshold, experimental results suggest that the electron temperature gradient scale length is close to the threshold value within internal transport barriers (ITBs).

Model for ETG mode threshold

Recently, a linear gyrokinetic code, GS2, has been used to solve the linear gyrokinetic equations [1]. A simple algebraic formula for the threshold has been derived from the numerical solution [1]:

$$\left(\frac{R}{L_{T_e}}\right)^{cr} = \max\left[(1+\tau)\left(1.33+1.91\frac{\hat{s}}{q}\right)(1-1.5\varepsilon)\left(1+0.3\varepsilon\frac{d\kappa}{d\varepsilon}\right), 0.8\frac{R}{L_n}\right], \tag{2}$$

where $\tau = Z_{eff}\,T_e/T_i$, $\varepsilon = r/R_0$, and κ is the elongation. The Eq (2) is applicable to standard core parameters, provided $\hat{s} \geq 0.2$ and $\alpha \leq 0.1$, where $\alpha = -q^2 R\, d\beta/dr$.

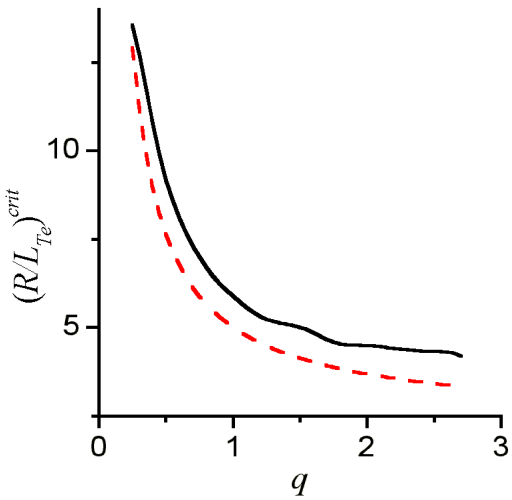
We compare the ETG thresholds defined by Eq (2) and the threshold found from a gyro-Landau-fluid (GLF23) transport model [2]. For this comparison, the nominal parameters are $T_e = T_i = 2.19\,\mathrm{keV}$, $Z_{eff} = 1.36$, $R/L_{Ti} = 0.1$, $R/L_n = 0.2$, $B_T = 1.8\,\mathrm{T}$, $\hat{s} = 0.77$, $q = 1.37$, and $\kappa = 1.31$. The GLF23 transport model yields results close to Eq (2) for the nominal parameters and reproduces the dependences on magnetic shear and safety factor (Fig. 1). However, the dependences on normalized density gradient (Fig. 2) and τ from GLF23 are different from

Eq (2). Since the dependence on the normalized density gradient can be important in the region of the ITB, it is questionable to use GLF23 for the electron transport within ITBs.

We combine the ETG linear threshold Eq (2) together with Eq (1) to produce the following new model:

$$\chi_e = \begin{cases} 0, & R/L_{Te} \le (R/L_{Te})^{cr} \\ \chi_e^{(0)} \tanh\left(C_{th}\left(R/L_{Te} - (R/L_{Te})^{cr}\right)\right), & R/L_{Te} > (R/L_{Te})^{cr} \end{cases} \quad (3)$$

where $\chi_e^{(0)}$ is given by Eq (1), and C_{th} is parameter, characterizing the width of transition region as a function of the electron temperature gradient.



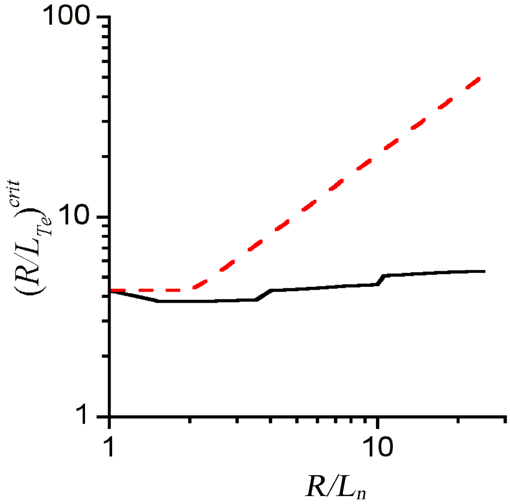


Figure 1. Dependence of the threshold value on the safety factor, q, for the GLF23 (solid line) and Jenko model (dashed line).

Figure 2.Dependance o f the threshold value on the normalized density gradient for the GLF23 (solid line) and Jenko model (dashed line).

Predictive simulations of the discharges with ITB

The BALDUR time-dependent 1-1/2 integrated modelling code predicts, as a function of magnetic flux surface, the time evolution of electron and ion temperatures, charged particle densities, and the poloidal magnetic flux density. In our BALDUR simulations, we use the 1999 version of the Multi-Mode model [6], which includes the Weiland transport quasi-linear fluid model for the ion-temperature-gradient (ITG) modes and the trapped electron modes (TEM). Expression (3) for the ETG diffusivity is implemented in the MM transport model and is applied to the JET discharges 40542 and 40847, and DIII-D discharges 84682 and 87031, which have ITBs in the ion transport channel. Results of the simulations for the JET discharge 40542 (Fig. 3) suggest that inclusion of the ETG electron thermal diffusivity in the form of Eq (3) results in an improvement of the electron temperature profile compared with results without the ETG contribution. When the modified expression (3) for the ETG electron thermal diffusivity is used, the ITB in the electron transport channel does not form, while the ITB in the ion transport channel remains in place, which is consistent with experimental data. The central electron temperature obtained with the model (3) is higher than the experimental one. The reason for this discrepancy is that the parameters C_e^{es} and C_e^{em} in Eq (1), which were obtained previously from calibration of model (1) against experimental data, may need to be recalibrated for the new model.

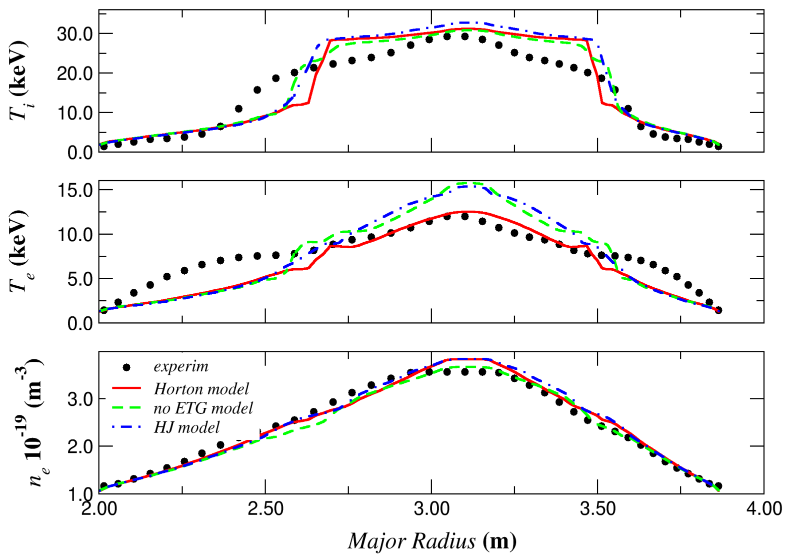


Figure 3. Results of the predictive simulations of the JET discharge 40542 with the MM transport model against experimental data (dotted curves). The MM model has: (a) no contribution from the ETG mode (dashed line); (b) contribution in the form of Eq (1) (solid line); (c) contribution in the form of Eq (3) (dash-dotted line).

Conclusions

Two models for the ETG threshold are studied and compared. The results of the GLF23 model and expression (2) derived from the linear gyrokinetic simulations diverge for large normalized density gradients, which can be important for analysis of the discharges with the ITBs. Combining the model for the electron thermal diffusivity [3], which was derived for the turbulence far from the ETG threshold, with the ETG threshold given by (2), we introduce a new model given by Eq (3). The new model is implemented in the integrated modelling code BALDUR and is applied to two JET and two DIII-D discharges with ITBs.

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This project has been funded in part by the National Academy of Sciences under the *Collaboration in Basic Science and Engineering Program/Twinning Program* supported by contract No. INT-0002341 from the National Science Foundation and by U.S. DoE contract DE-FG02-92-ER-54141. The contents of this publication do not necessarily reflect the views or policies of the National Academy of Sciences or the National Science Foundation, nor does mention of trade names, commercial products or organization imply endorsement by the National Academy of Sciences or the National Science Foundation.