

The role of electron-driven microinstabilities in particle transport during electron Internal Transport Barriers

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Abstract

Experimental results obtained in TCV electron Internal Transport Barriers (eITBs) show a strong coupling between the plasma density and the electron temperature logarithmic gradients [1]. The plasma density is sustained by an inward thermodiffusive pinch whose theoretical understanding has not been achieved yet. The level of particle diffusivity, as estimated in transient transport experiments, indicates anomalous transport as the main mechanism to create this pinch. On the other hand, a clear improved heat and particle transport confinement is observed. Gyrokinetic calculations of the pinch coefficients are performed in the framework of quasi-linear theory, neglecting electromagnetic effects and assuming zero collisionality, limits which are reasonable for an eITB; core particle sources and impurities are also neglected. The role of non-adiabatic passing electrons is taken in to account and shown to be negligible. The coupling between density and temperature is provided via trapped electrons driven thermodiffusion which is maximized near the transition between ITG-dominated to TEM-dominated turbulence. This regime is obtained in a plasma characterized by large temperature and density logarithmic gradients through different stabilizing mechanisms discussed here.

Introduction

Peaked density profiles are usually observed during the steady-state operation of eITBs in TCV [1]. The density logarithmic gradient is found to be correlated with the electron temperature logarithmic gradient with a robust, in the sense of experimental reproduction, ratio of about 0.4-0.5, i.e. $R/L_n \sim 0.45R/L_{Te}$. Neoclassical transport is still negligible in these eITB scenarios [2] and thus we will resort to turbulence codes to elucidate the background physics. The gyrokinetic code GS2 [3] is employed to understand how steady-state density profiles are sustained by the anomalous pinch for typical eITB parameters. The eITB scenario discussed here involves the reversal of the magnetic shear and very strong electron heating, assessing the role of the Trapped Electron Mode (TEM) that is usually associated with flattened density profiles [4].

Theoretical background

The steady-state density profile, in the framework of quasi-linear turbulence theory, is given by the general formula:

$$\frac{R}{L_n} = -R\frac{V}{D} = -C_T\frac{R}{L_{Te}} - C_P \quad (1)$$

where V and D are the pinch velocity and diffusion coefficient respectively. The term $-C_T\frac{R}{L_{Te}}$ is called turbulent thermodiffusion (THD), while the other off-diagonal term has been historically called 'turbulent equipartition' (TEP) [5]; in this context the latter contains all the off-diagonal contributions to particle transport which are not linearly proportional to R/L_{Te} . The two coefficients are evaluated with GS2 via a trace-particle method solving a linear system to find C_T and

C_P . Note that for a single ballooning mode (identified by the value of the poloidal wavenumber $k_y \rho_i$) the two coefficients are *independent* of the mixing length rule for $|\Phi|^2$ (i.e. the turbulence level determines fluxes but not source-less steady-state profiles), allowing for a direct comparison with the experiment without assumptions on non-linear saturation phenomena. The sign convention, as seen from formula 1, is such that negative values of the coefficients give inward pinch contribution, while positive values contribute outward. Each coefficient contains contributions from both passing and trapped particles. Without trapping, and starting from the ballooning-averaged linearized gyrokinetic equation coupled with quasineutrality, it is possible to evaluate analytically the thermodiffusion coefficient for electrons to be $-C_T \sim 0.5$, in agreement with the experimental observations. However, the trapped fraction is $f_t \sim 0.4$ at mid-radius where the maxima of the logarithmic gradients are usually located. Trapped electrons contribute with a strong outward pinch for a mode rotating in the electronic direction, almost reversing the sign of C_T for strong a TEM. We then expect the TEM to be marginally stable for the particle barrier to exist. As will be shown later, C_P is negligible in these scenario, allowing us to concentrate on the behavior of C_T only.

Understanding the density barrier

The simulations employ parameters typical of an eITB obtained in the TCV tokamak: $R/L_{Te} = 16$, $T_e/T_i = 2.5$, $\hat{s} = -0.7$, $q = 2.7$, $\varepsilon = 0.11$, $\alpha_{MHD} \sim 1.5$. R/L_n is scanned to find the self-consistent steady-state point of zero particle flux. R/L_{Ti} and α_{MHD} are varied to test the response

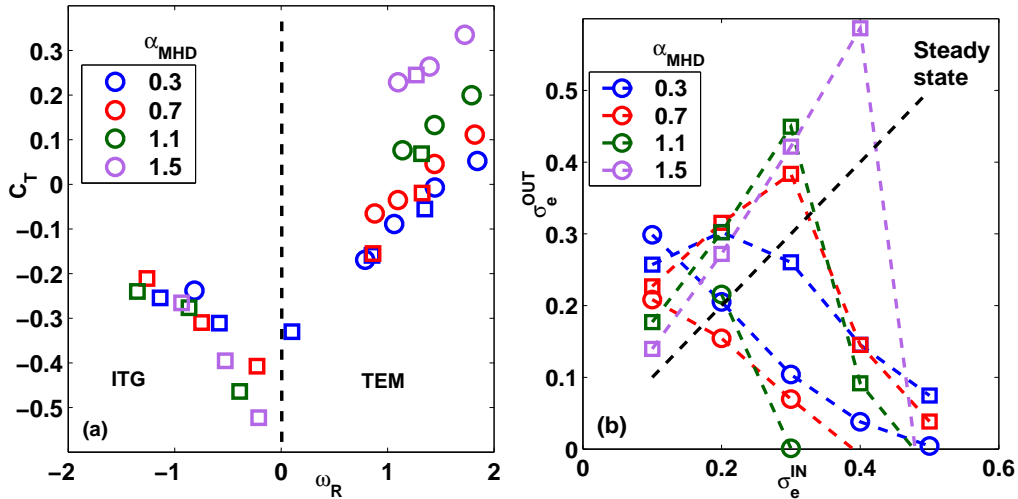


Figure 1: **a)** Thermodiffusion coefficient C_T versus the mode frequency ω_R for different values of α_{MHD} obtained with GS2, circles represent $L_{Te}/L_{Ti} = 0.5$ and squares $L_{Te}/L_{Ti} = 0.8$; **b)** Steady-state diagram for $\sigma_e = L_{Te}/L_n$: $\sigma_e^{OUT(PUT)GS2} > \sigma_e^{IN(PUT)GS2}$ implies an inward flux and subsequent increase of σ_e , $\sigma_e^{OUT} < \sigma_e^{IN}$ implies an outward flux, $\sigma_e^{OUT} = \sigma_e^{IN}$ (black dashed) provides the steady-state value when intersecting the different curves (the intersections are *stable* steady-state points)

of TEMs and their stabilization. The normalized poloidal wavenumber is fixed at $k_y \rho_i = 0.3$ where the spectrum of γ/k_\perp^2 peaks for these parameters. We neglect impurity physics assuming $Z_{eff} = 1$, reminding that in the experimental discharges analyzed we observe a global $Z_{eff} \sim 3$, which spatial profile is however not known. The calculations are made in the electrostatic and collisionless limit, without core particle sources. The simulations indicate that (as soon as C_P is negligible) C_T is maximized, in the inward direction, around the ITG-TEM transition, i.e. when $\omega_R \sim 0$, figure 1(a). The maximum value of $-C_T$ increases with α_{MHD} , which is then a favorable parameter. We note also that a higher α_{MHD} gives a sharper transition in the behavior of C_T .

Figure 1(b) shows the steady-state diagram, using $\sigma_e = L_{Te}/L_n$ as parameter (the experimental value is $\sigma_e \sim 0.45$). Each curve is interpreted as the following: at low R/L_n the particle flux is directed inward and so the density logarithmic gradient builds up, as soon as TEMs are destabilized the curve has a negative slope and the flux changes sign. The (stable) steady-state point is located at the intersection of the calculated curves and the 45° line. At high values of α_{MHD} the steady-state point moves toward higher values of σ_e , but it appears as a 'threshold' phenomena more than a continuous process. R/L_{Ti} seems to be fundamental in providing a more efficient effect of α . Figure 2(a) shows the TEM threshold frequency shift due to α_{MHD} stabilization and

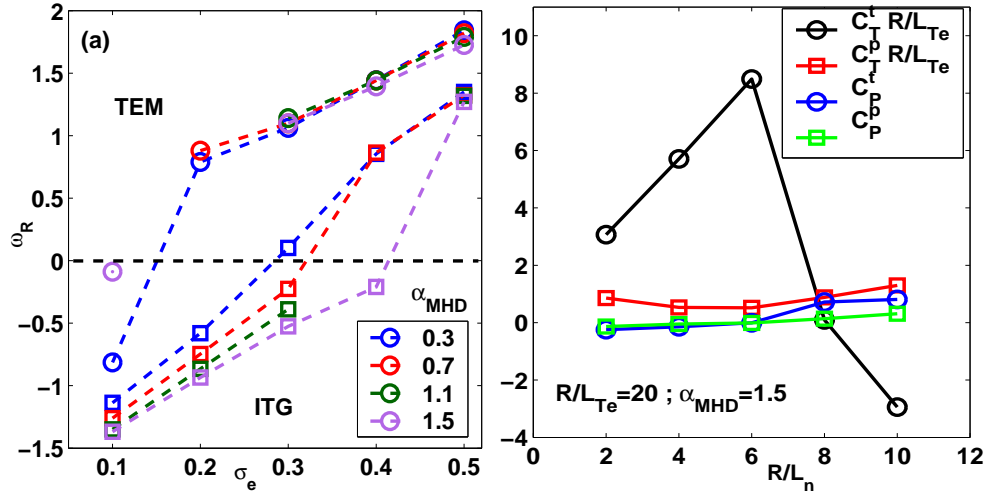


Figure 2: **a)** TEM threshold shift in frequency shown as mode frequency ω_R vs σ_e for different values of α_{MHD} , as before circles have $L_{Te}/L_{Ti} = 0.5$ and squares have $L_{Te}/L_{Ti} = 0.8$; **b)** Example to show that trapped particle driven thermodiffusion (represented by $C_T^+ R/L_{Te}$) is the key mechanism to sustain the density barrier.

favorable L_{Te}/L_{Ti} effect. Figure 2(b) shows that the TEP contribution C_p in these simulation is found to be negligible, as the contribution of passing electrons.

Combined s - α_{MHD} effect

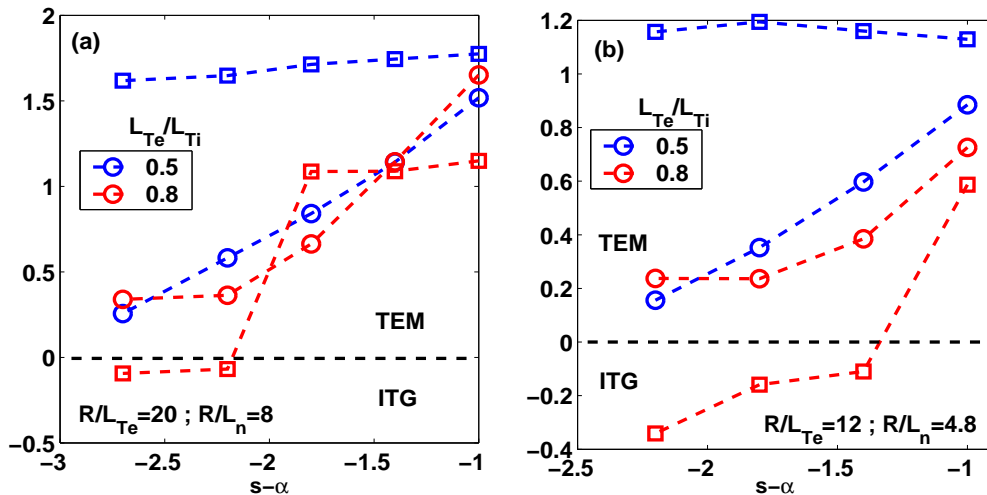


Figure 3: Growth rate γ (circles) and frequency ω (squares) versus $s - \alpha_{MHD}$ for two different values of the ratio between ion and electron temperature logarithmic gradients, shear is fixed at $s = -0.7$.

The barrier existence is provided by the stabilizing effect of both reversal of magnetic shear s and increased plasma pressure via the α_{MHD} parameter. The magnetic curvature drift in the ballooning formalism is expressed as: $\omega_{\text{D}} \approx \cos \theta + (s\theta - \alpha \sin \theta) \sin \theta$, which, for $\theta \sim 0$ becomes $\omega_{\text{D}} \approx 1 + (s - \alpha - 1/2)\theta^2$. Stabilization becomes stronger as the parabola becomes more 'peaked', i.e. as $|s - \alpha| \Rightarrow \infty$. However, the efficacy of $s - \alpha$ in changing the mode real frequency ω_{R} depends on the value of $L_{\text{Te}}/L_{\text{Ti}}$, while the growth rate seems to decrease similarly in the two cases. In figures 3 we see that, at fixed gradients, the mode is more and more stable combining magnetic shear reversal and increasing Shafranov shift. The mode being a TEM at small absolute values of $s - \alpha_{\text{MHD}}$, it switches to ITG when $s - \alpha_{\text{MHD}}$ stabilization is sufficiently strong. We require either a large negative shear or a large Shafranov shift. As said before, the switching to ITG is given only provided that the value of R/L_{Ti} is not too small compared to R/L_{Te} . It is interesting to note that, contrary to the temperature barrier, which is built by a decrease in the heat flux at constant input power, linked to the decrease in the mode growth rate γ , the density barrier sustainment is strongly related to the behavior of the mode frequency ω_{R} and very poorly on γ .

The role of impurities, collisionality and ions

Preliminary results show that TEMs are more unstable due to the impurity driver for values of $Z_{\text{eff}} > 2$, and thus the density logarithmic gradient is diminished. Collisionality seems to play a similar role in decreasing the efficacy of trapped particles in carrying the thermodiffusive inward pinch. Ions experimental parameters are presently unknown; to make a quantitative comparison with theory, a future experimental TCV campaign will be devoted to this issue.

Discussion of the results

The gyrokinetic simulations of this eITB scenario support the interpretation of the observed density barrier as sustained by a dominant anomalous thermodiffusive inward pinch as was expected in [1]. This inward pinch is maximized at the ITG-TEM transition, i.e. when the mode real frequency ω_{R} approaches zero, where the pinch coefficient C_{T} is found to be consistent with the experimental values. To obtain this, TEMs must be strongly stabilized, as normally in positive shear scenarios the threshold $R/L_{\text{n}} \sim 5$, while in TCV eITBs values of $R/L_{\text{n}} \sim 12$ can be achieved. The combination of negative magnetic shear and high values of α_{MHD} can shift the TEM threshold up to the desired values of R/L_{n} . Another requirement is that the ion to electron temperature logarithmic gradients ratio be of order ~ 0.8 . The theoretical picture drawn in this work is qualitatively consistent with the experimental observations although the physical model does not contain nonlinear and electromagnetic effects. However, electromagnetic effects are not expected to play a role since $\beta_{\text{T}} \sim 10^{-3}$. As a last remark, these results should apply also near the q_{min} (or $s = 0$) position, not tractable by a local ballooning gyrokinetic code (limited to $|s| > 0$).

Acknowledgements

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