Simulations of Transport Barrier Formation by RF-wave Power without Shear Flow in TCABR

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I. Introduction

Transport barriers are recognized as a very effective means of increasing the energy confinement time in toroidal magnetized plasmas and it is quite likely that next step experimental fusion reactors like ITER will rely on their formation in order to achieve large Q values. The most common mechanism for the formation of transport barriers is linked to zonal flows (a shear flow), but they are also created by a negative magnetic shear. Zonal flows can be produced by injecting RF waves which either transfer directly their momentum to the plasma or heat preferentially particles with momentum in a given direction. The shear flow then reduces turbulence by breaking turbulent eddies which decreases the associated transport. There is, however, a different way of suppressing turbulence without the need of shear flow, that can also be driven by RF waves. This novel mechanism was proposed in [1] for the case of ITG modes and is based on the effect of the ponderomotive force of the RF wave on the ITG mode stability. In order to test the effectiveness of this mechanism, here we estimate the transport coefficients associated with ITG modes including the concomitant RF stabilization, which are then used in transport simulations to explore the barrier formation in the tokamak TCABR.

II. Stability analysis

We take a plasma equilibrium in a slab sheared magnetic field, $\mathbf{B}(x) = B_0\hat{z} + B_0 x/L_s\hat{y}$, with L_s the shearing scale length and x the radial coordinate. All equilbrium plasma variables are only functions of x. A two-fluid model is adopted and perturbations of the form $\phi(\mathbf{r},t) = \phi_1(x)\exp[i(k_y y + k_z z - \omega t)]$ are applied assuming the regime of small gyroradius, $k_\perp \rho_i \ll 1$, where ρ_i is the ion gyroradius. The drive for the instability is the ion temperature gradient (ITG) which is responsible for the diamagnetic fluid drift $\mathbf{v}_D = (c/eBn_i)\hat{b} \times \nabla_\perp p_i$. Additionally, the presence of RF waves is included through the effect of the associated ponderomotive force $\mathbf{F}_{RF}$, which gives rise to a drift velocity, $\mathbf{v}_{RF} = (c/B)\mathbf{F}_{RF} \times \hat{b}$. No flow generation by RF waves is included so the resulting reduced transport cannot be attributed to it. The perturbed equations of continuity, parallel momentum and adiabatic pressure evolution for ions, in the linear approximation, can be reduced to the following equation for the electric potential [1]

$$\frac{d^2\tilde{\phi}}{dx} + \left(T + Qx + Mx^2\right)\tilde{\phi} = 0, \tag{1}$$

where

$$T = -k_y^2 + \frac{1 - \Omega + \frac{F_{RF0}}{k_y v_D}(1/L_{RF} + v_D)}{\Omega + K}, \qquad Q = \frac{\frac{F_{RF0}}{k_y v_D L_{RF}}(1/L_{RF} + v_D)}{\Omega + K}$$

$$M = \frac{s^2}{\Omega^2\left(1-\frac{\Gamma s^2 x^2}{\tau\Omega^2}\right)} + \frac{F_{RF0}}{2k_y(\Omega+K)L_{RF}^2}$$

Here, x is measured from the mode rational surface and all quantities are normalized according to $\tilde{\phi} = e\phi/T_e$, $\tilde{v} = v/c_s$ and distances to a length of the order of the density scale length L_n. The parameters used are: $\tau = T_e/T_i$, $s = L_n/L_s$, $K = (1+\eta_i)/\tau$, $\Omega = \omega/(k_y v_D)$ $\eta_i = d\ln T_i/d\ln n$ and Γ is the ratio of specific heats. To model the ponderomotive force an expansion in terms of a Taylor series was assumed $F_{RF}(x) = F_{RF0}(1 + x/L_{RF} + (x/L_{RF})^2$ so that the wave intensity has a maximum at the mode rational surface and L_{RF} is the length scale for the RF wave and may be realted to the deposition profile width.

When $\Gamma = 0$ Eq.(1) reduces to a simple Weber equation whose properties and solutions are well known. The solvability condition gives the dispersion relation $Q^2/4M = T - i\sqrt{M}$, which can be solved for the real and imaginary parts of $\omega = \omega_r + i\gamma$. In [1] it is shown that the growth rate γ decreases as F_{RF0} is increased and when L_{RF} is reduced, for a given value of $k_y\rho_i$. The real frequency is also reduced in absolute value under the same conditions. As a function of k_y, γ presents a maximum for a certain value $k_{y,M}$ which would give the effective growth rate for the overall mode, and the value of $k_{y,M}$ increases with F_{RF0}. For $F_{RF0} \geq 0.1$ and $L_{RF} \leq 0.1$ the mode is almost completely stable and has $\omega_r \approx 0$. For finite Γ the dispersion relation cannot be found analytically but the results obtained numerically are qualitaively the same.

III. Transport barrier formation

In order to obtain the anomalous diffusion coefficient we use a mixing length estimate based on the growth rate γ for the unstable mode and its radial scale length, Δ. Accordingly, the coefficient would be given by, $D_a = \gamma\Delta^2$. In [1] the growth rate for the ITG mode is found by numerically solving the dispersion relation and it is presented as a function of the normalized poloidal wavenumber, $k_y\rho_i$. The values of γ are in a range of the order of $0 - 0.3\omega_{*e}$, where ω_{*e} is the electron drift frequency. We take the maximum value, $\gamma(k_{r,M})$, for the evaluations and use the corresponding value of the real part for the same wavenumber $\omega_r(k_{r,M})$ where this is needed. We estimated the mode width from the structure of the eigenfunctions that describe it. They are determined by the differential equation (1), and the properties of this Weber equation give that the solutions are localized in a region of width $\Delta = (2\sqrt{M})^{-1/2}$, with M defined after Eq.(1). Therefore, the diffusion coefficient, in terms of the normalized growth rate $\hat{\gamma} = \gamma/\omega_{*e}$, is

$$D_a = [\hat{\gamma}/2\sqrt{M}]\omega_{*e} \quad (2)$$

This expression is used for the particle diffusion as well as the heat conductivities for both, ions and electrons but each one is multiplied by a constant to be determined by fitting to experimental values.

Transport analysis in performed using the Astra code [2] using transport coefficients as linear combinations of the neoclassical values and an anomalous component given

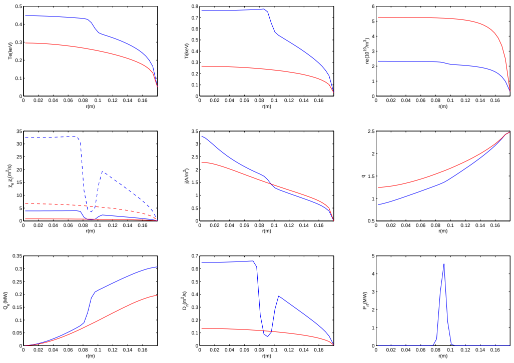

Figure 1: Radial profiles before (red) and after (blue) RF injection

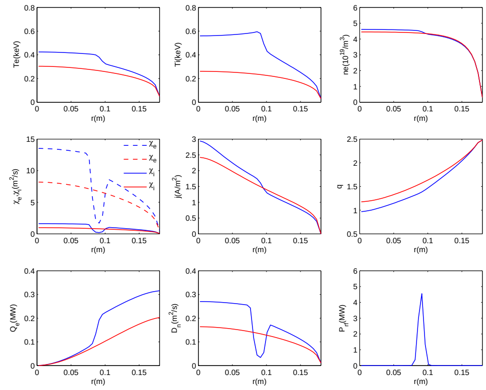

Figure 2: Radial profiles for RF wave injection and a rise of 35 % in gas puffing

by (2), the latter being the dominant part. The Astra code includes an equation for neutral particles providing a source of plasma particles. First we run Astra code with no RF wave and adjust the free parameters in order to fit the typical values for the density and temperatures measured in a tokamak. For this we choose the Brazilian tokamak TCABR since it is a good candidate to test the theoretical results obtained here in an actual machine which uses Alfvén wave heating. So, we take the following device and plasma parameters: $R_0 = 61.5cm, a = 18cm, I_p = 120kA, B_T = 1.1T, n_e(0) = 3 \times 10^{13} cm^{-3}, T_e = 500eV$ and $T_i = 300eV$. The anomalous diffusivities are scaled as, $D_n = k_n D_a, \quad \chi_e = k_e D_a, \quad \chi_i = k_i D_a$. Initially, we set $F_{RF0} = 0$, to get the plasma radial profiles with no RF wave injection. The constants k_j $(j = n, e, i)$ are varied in order to fit the experimental profiles. For TCABR it is found that the appropriate values are $k_n = 0.3, k_e = 15, k_i = 1.8$. Using TCABR parameters, the corresponding form of the anomalous diffusion can be written as,

$$D_a = D_{a0}\Gamma_a \left(1 + \frac{F_{RF0}(K_a/s)^2(\hat{\omega}/\hat{k})^2}{2\hat{k}(K_a\hat{\omega}/\hat{k} + k)L_{RF}^2}\right)^{-1/2}, \quad \text{with} \quad D_{a0} = 5.5\left(\frac{T_i}{0.4}\right)^{3/2} \hat{\omega}\hat{k}\ \frac{m^2}{s} \quad (3)$$

the no-RF-power diffusivity, and $\Gamma_a = (\hat{\gamma}/0.31)(\hat{\omega}/0.3)(\hat{k}/0.5)$, $\hat{\omega} = \omega/\omega_{*e}$, $\hat{\gamma} = \gamma/\omega_{*e}$, $\hat{k} = k_y \rho_i$ and $K_a = \omega_{*e}\rho_i/v_D$. In writing Eq.(3) the normalization length scale is taken as $L = \rho_i$ which together with the normalization for ω which is ω_{*e}, give the dependence $\sim T_i^{3/2}$. It can also be considered a case where D_{a0} is independent of T_i as a comparisson point. The starting profiles are taken with a parabolic shape for the three quantities, $n_e(r), T_e(r)$ and $T_i(r)$, and the code is advanced in time up to the point when a steady state is reached, where we can say that a self-consistent equilibrium has been established.

In Fig. 1 we show the profiles for the equilibrium state (in red) of several plasma parameters, namely, electron and ion temperatures, $T_e(r), T_i(r)$, electron density, $n_e(r)$, electron and ion heat diffusivities, χ_e, χ_i, current density, $j(r)$, safety factor, q, electron heat flux, Q_e, particle diffusivity $D_n(r)$ and RF power P_{RF}. When $P_{RF} = 0$ the profiles have the typical shapes for an ohmic discharge. The blue lines in Fig.1 show the result of turning on the RF power, for which we used a gaussian deposition profile for the ponderomotive force: $F_{RF0}(r) = \alpha P_{RF} \exp\left(-[(r-0.5a)/0.03a]^2\right)$. This represents absorption of Alfvén waves as in TCABR, in a narrow region $L_{RF} = 0.03a$ (in order to have a clearer manifestation of barrier formation). The power is $P_{RF} = 0.1MW$ and α is a free parameter (determining the actual ponderomotive force value), chosen to show that the barrier formation is plausible. In the new steady state the effect of the stabilized modes is shown by the clear formation of an ITB. The diffusivities have a deep reduction from their previous values around $r = a/2$, where P_{RF} is peaked, as a result of the mode stabilization. The concomitant effect on the temperatures and density profiles is to form a pedestal-like region about the point $r = 0.5a$ having a large gradient, with increased values of T_e and T_i within. This is indicative of the appearance of an internal transport barrier. However, since the expression in Eq.(3) was used the diffusivities increase near the center due to the large ion temperature rise associated with the barrier formation. Also we notice a decrease in the density even when there is the signature of a particle barrier at $r = a/2$, but this is due to the fact that the central temperatures increase while the pressure $p = n_e(T_i + T_e)$ stays at a fixed value.

In order to maintain a high density it would be necessary to supply additional fuel as the RF power is injected. The effect of increasing the influx of neutral particles by gas puffing in 30 % is shown in Fig. 2. In this situation all plasma quantities have an increment at the center while the large gradient zone at the RF wave absorption position is still there. This has the features of a true improved confinement regime. Another consequence of the central temperature rise is an increment in the current density around the center due to the temperature dependence of the electrical conductivity. This results in a reduction of the central q value below one. The consequence is that the plasma will develop sawtooth oscillations which were not present initially.

IV. Conclusions

Evidence for the formation of a transport barrier is found in transport simulations of a tokamak like TCABR, when RF power is inyected in such a way as to stabilize the ITG modes. No sheared rotation is present, indicating that the ponderomotive force of RF waves can give rise to transport suppression without zonal flows. A simultaneous increase of density and ion and electron temperatures can be achieved by adjusting gas puffing into the machine.

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