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INTRODUCTION

Among the various instabilities which could explain the anomalous electron heat transport observed in tokamaks during additional heating, a microtearing turbulence ([1], [2]) is a reasonable candidate since it affects directly the magnetic topology. This turbulence may be described in a proper frame rotating around the majors axis by a static potential vector

$$A(r, \theta, \varphi) = \sum_{\ell} A_{\ell}(r)\, e^{i(\ell\theta + m\varphi)} + CC$$

(a single m is assumed to simplify). In that frame, an average electric field $-\frac{\partial U}{\partial r}$ confines hot electrons. An ergodic layer exists when the islands chains produced by each $A_{\ell}(r)$ exhibit a width $2\delta_I$ larger then the distance δ_r between two resonant surfaces $m + \frac{\ell}{q(r_{\ell})} = 0$. The field lines become stochastic with an exponential divergence scale $L \sim \frac{L_s}{K_{\theta}\delta_I}$ (L_S is the shear length, $K_{\theta} = \frac{\ell}{r}$), which is also the parallel scale of the fluctuations. In such strong non linear regimes, the flow of electrons along the stochastic field lines induces a current $I = \sum_{\ell} I_{\ell}(r) e^{i(\ell\theta + m\varphi)} + CC$. The point is to know whether this current can sustain the turbulence, namely verify the Ampère law for each mode :

$$-\frac{d^2 A_{\ell}}{dr^2} + K_{\theta}^2 A_{\ell} = \mu_o I_{\ell} \qquad (1)$$

The mecanisms of this self-consistency, involving the combined effects of the thermal diamagnetism and of the electric drift $V_{E\theta} = \frac{1}{Bo}\frac{\partial U}{\partial r}$ are presented here.

1. BASIC EQUATIONS

We neglect the electric fluctuations superimposing to the average field $-\frac{\partial U}{\partial r}$. However, these fluctuations may stabilize the microtearing modes if the ion response is MHD. This typically forbids radial scales larger than the ion Larmor radius ρ_i. The electron distribution function $f(r, \theta, \varphi, V_{\perp}^2, V_{\parallel})$ is solution of a Fokker-Planck equation

$$V_{\parallel} \nabla_{\parallel} f + V_{E\theta} \frac{1}{r}\frac{\partial f}{\partial \theta} - \frac{e}{m} \nabla_{\parallel} U \frac{\partial f}{\partial V_{\parallel}} = C(f) + D\Delta f + S \qquad (2)$$

where $\nabla_{\parallel}$ is the derivative along the actual field lines, S is a source, C(f) is the $V_{\parallel}$ collision operator and $D\Delta f$ a small diffusion operator. These operators avoid small scales singularities due to the stochasticity of field lines and ensure that f is near Maxwellian. Non linear effects are expected to be important if the transit time $\frac{L}{V_{\parallel}}$ is shorter than the diffusion time $\frac{\delta_I^2}{D}$ and the electric drift extraction time $\frac{1}{K_\theta V_{E\theta}}$

Anticipating that $\frac{e}{T}\frac{dU}{dr} \sim \frac{dn}{ndr} \sim \frac{1}{L_n}$ this last condition is equivalent to $\boxed{\frac{L_S}{L_n}\rho_e << \delta_I}$

(ρ_e is the electron Larmor radius)

It allows to treat the equation (2) perturbatively, writing $f=f_o+f_1$

$$\begin{cases} T(f_o) = S & (3) \\ T(f_1) = - V_{E\theta}\frac{1}{r}\frac{\partial f_o}{\partial\theta} & (4) \end{cases}$$

with :

$$T. = V_{\parallel}\nabla_{\parallel}. - \frac{e}{m}\nabla_{\parallel} U \frac{\partial .}{\partial v_{\parallel}} - C(.) - D\Delta$$

It can be proved [3] that f_o produces a current I_o which is in quadrature of phase with A and which must therefore vanish in view of the Ampère law. So, only the current I_1 derived from f_1 can sustain the turbulence. However, the correlations $\int dr\, A_\ell^*(r)\, I_{1\ell}(r)$ cancel in the collisionless regimes when $A_\ell(r)$ is assumed to be constant in the resonant layer $|r-r_\ell| \lesssim \delta_I$ [3]. This feature, already found in the linear regime, holds at any velocity $V_{\parallel}$ and is not consistent with the constraint

$$\int \left(\left|\frac{dA_\ell}{dr}\right|^2 + \left|K_\theta A_\ell\right|^2 \right) dr = \mu_o \int I_\ell(r)\, A_\ell^*(r)\, dr \qquad (5)$$

deduced from the Ampere law (1). Friction effects are therefore essential in the mode destabilization for the constant $A_\ell(r)$ case.

2. PARALLEL CURRENTS IN QUADRATURE AND IN PHASE WITH A

The computation of f is performed by dividing the velocity phase space in small volumes $d_3 V_K$ centred on $(V^2_{\perp k}, \pm V_{\parallel k})$. For each group, the equations (3,4) provide the activity $N_k(r,\theta,\varphi) = n_k(r,\theta,\varphi) + \bar{n}_k \frac{e}{T} U(r)$ (n_k is the density of the considered group, $\bar{n}_k$ its average value over the layer) and the parallel flow I_k (r, θ, φ) through a numerical code. Solving first eq. (3), the functions N_{ok}, I_{ok} are found.

According to the above remarks, the current $I_o = \sum_k I_{ok}$ is in quadrature with A and must cancel. This is achieved by adjusting the electric field $-\frac{\partial U}{\partial r}$ [3].

$$-\frac{e}{T}\frac{dU}{dr} = \frac{1}{n}\frac{dn}{dr} + \frac{\alpha}{T}\frac{dT}{dr} \qquad (6)$$

where $\frac{dn}{ndr}$, $\frac{dT}{Tdr}$ are the average density and temperature gradients, $\alpha = \frac{1}{2}$ (resp. $\alpha = \frac{5}{2}$) in the collisionless (resp. collisional $\frac{\nu th\ L}{Vth} > 1$) regime ($V_{th}$ and ν_{th} are the electron thermal velocity and collision rate).

The source $\alpha \frac{\partial f_o}{\partial \theta}$ with appears in the r.h.s of eq. (4) corresponds for each groupe k to a particle source $S'_k \alpha - V_{E\theta} \frac{1}{r} \frac{\partial Nok}{\partial \theta}$ and a parallel momentum source $S''_k \alpha - V_{E\theta} \frac{1}{r} \frac{\partial Iok}{\partial \theta}$. The source S'_k by short circuiting along the flux lines and S''_k acting as a ponderomotive force induce a parallel fluxes $I'_{1k\ell} + I''_{1k\ell}$ which are shown numerically to be localized near the resonant surface $r = r_\ell$ over a width $\sim \delta_I$. In the sense of the constraint (5), the electric current $I'_{1k\ell}(r)$ is destabilizing (positive r.h.s integral in (5)) while $I''_{1k\ell}(r)$ is stabilizing. As expected, the two currents cancel each other in (5) in the constant $A_\ell(r)$ collisionless regimes. A crucial point is that the collisionless current I''_{1k} is more sensitive to collisions than the current I'_{1k} and is found numerically to be negligible when the collision rate ν_k is larger than $\frac{Dact}{\delta_I^2}$, where $D_{act} = D + D_{erg}$ is the actual diffusion coefficient in the ergodic layer. The groups k for which this condition is satisfied perform a current $I_1 = \sum_k I'_{1k}$ which is destabilizing.

3. CONSISTENCY OF THE TURBULENCE

The computed I_1 introduced in the Ampere constraint (5) (using the vacuum shape $A_\ell(r_\ell)\ \exp - |K_\theta(r-r_\ell)|$ of the potential vector outside the current layer) gives the value of

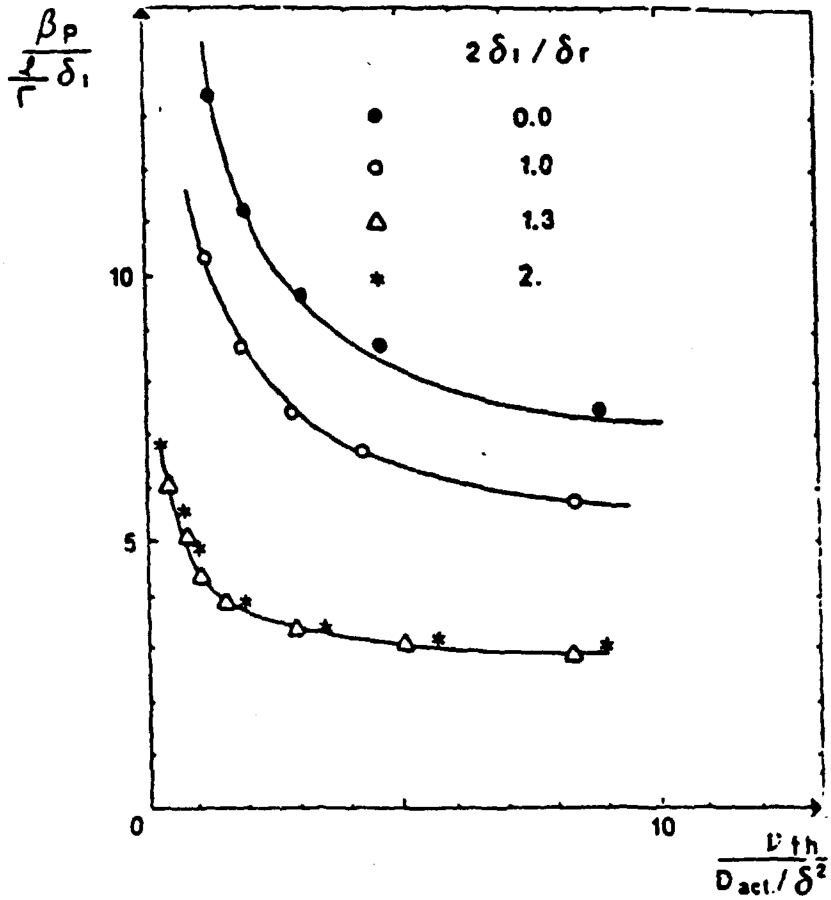
$$\frac{\beta_P}{K_\theta \delta_I} \quad (\beta_P = 2\ \eta\ (2+\eta)\ \frac{nT}{B_o^2}\ \mu_o\ \frac{L_S^2}{L_n^2}\ ,\ \eta = \frac{dLogT}{dLogn}\ )$$

as a function of the Chirikov parameter $\frac{2\delta_I}{\delta_r}$ and the collisionality parameter $\frac{\nu th}{Dact/\delta_I^2}$ where D_{act} is now the thermal actual diffusion coefficient. (see Fig. 1).

CONCLUSIONS

From the fig. 1, the diffusion coefficient D_{act} is seen to be of order $\nu_{th}\ \delta_I^2$. The electric fluctuations which have been neglected impose that in fact $\delta_I \lesssim \rho_i$ so that D_{act} scales as $\nu_{th}\ \rho_i^2$. This is comparable to the experimental anormal electron heat flux only in the edge of nowadays tokamaks. Our present research is devoted to collisionless microtearing regimes with non constant $A_\ell(r)$ wich seem possible according to preliminary calculations.

Fig. 1



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