

# ANALYSIS OF PEP DISCHARGES IN TORE SUPRA

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## 1. Introduction

The Pellet Enhanced Performance (PEP) mode is a transient improved confinement obtained by injecting high speed pellets in the plasma core of a tokamak, using a strong additional heating. This regime has been interpreted in the frame of the Rebut-Lallia-Watkins transport model in JET [1], which outlines the role of a reversed magnetic shear profile. In TFTR [2], density peaking appears to be the dominant parameter, for no clear reversed shear has been observed. This behaviour can be understood as a stabilization of drift waves by various mechanisms. Density peaking is indeed known to stabilize ion modes, and the beneficial effect of a negative magnetic shear on trapped particle curvature driven modes has long been mentioned in the literature [3]. But  $\mathbf{ExB}$  rotational shear could also have a role to play in these discharges with high pressure gradients. Indeed, non-linear simulations have shown that  $\mathbf{ExB}$  is able to stabilize the turbulence when the shear rate  $\gamma_E \approx r/q(qE_r/rB)'$  is comparable to the maximum linear growth rate of the instability [4] ( $r$  is the minor radius,  $q$  is the security factor,  $E_r$  is the radial electric field and  $B$  is the magnetic field).

We analyze PEP mode in terms of drift wave stability, with a linear model for pure electrostatic modes (low- $\beta$  limit), and large growth rates. Finite Larmor radius effects and collisions on trapped particles are implemented. This model involves trapped particles and passing ions, with adiabatic passing electrons. It accounts for the mechanisms due to density peaking, and high or low magnetic shear effects.  $\mathbf{ExB}$  shear stabilization is implemented through the formula  $\gamma = \gamma_i - |\gamma_E|$ , where  $\gamma$  is the linear growth rate calculated with our model. The radial electric field is deduced from a comprehensive calculation of neoclassical equilibrium. This model allows a quick determination of the spectrum of unstable drift waves over the whole minor radius. An heuristic diffusion coefficient is used to compare the PEP and L-mode phases in a given discharge.

We find that the improved confinement in Tore Supra PEP mode can be explained by the stabilization by short density gradient scales and  $\mathbf{ExB}$  shear, without invoking a modification of the current profile. The question of reversed magnetic shear, which was not completely elucidated in TFTR, is also uncertain in Tore Supra. But the profile of bootstrap current is in agreement with a flat current profile in the core. In this case, we find that drift waves are deeply stabilized in the region of low shear.

This paper is organized as follows : a parametric analysis of drift waves stability as function of collisionality, density peaking, and magnetic shear is presented in Section 2; the stability of a Tore Supra PEP mode is investigated in Section 3, and a conclusion follows.

## 2. Stability analysis

We investigate the role of collisionality, density peaking and magnetic shear  $s = r\nabla q/q$  on drift wave stability. A heuristic diffusion coefficient is used to compare the different cases. It is defined as :  $D_h = C \sum_n N_{mn} \gamma_n \lambda_n^2$ , where  $\gamma_n$  is the growth rate associated to the toroidal wavenumber  $n$ ,  $\lambda_n = \min(w_n, 1/k_\theta)$ ,  $w_n$  is the mode width, and  $N_{mn}$  is the number of poloidal wavenumbers  $m$  such that  $m = -nq$  within the radial interval  $\Delta r$ . We have  $N_{mn} = E(\Delta r/|d|)$ , where  $E(x)$  is the integer part of  $x$ , and  $d = 1/(n\nabla q)$ . The constant  $C$  is adjusted arbitrarily to  $10^{-3}$ .

For all calculations in this paragraph, the working gas is deuterium, the minor radius is  $a = 0.72$  m, the major radius  $R = 2.28$  m, and the magnetic field  $B = 3.85$  T. Electron and ion temperatures are taken to be equal. This hypothesis is representative of PEP mode conditions, in which equipartition is strong.  $\Delta r$  will be taken equal to 0.1 m.

### 2.1. Collisions

We consider first the effect of collisional detrapping, in a fixed total pressure plasma. In the case presented in Figure 1 (left), the density of reference ("n<sub>ref</sub>") is  $10^{20}$  m<sup>-3</sup>, and the temperature of reference is 1.6 keV;  $q = 1.45$ ,  $s = 0.32$ ,  $r/a = 0.45$ ,  $R/L_p = 16$ , and  $R/L_n = 10.5$ , where  $L_y = -y/\nabla y$  is the gradient length of  $y$ . Since collisionality is proportional to  $n_e/T_e^{3/2}$ , the relative change is  $v/v_{ref} = (n_e/n_{ref})^{5/2}$ . The maximum linear growth rate decreases with increasing collisionality, and the spectrum is modified : low wavenumbers are stabilized, whereas high frequency modes are excited by collisional detrapping. A decrease of the diffusion coefficient  $D_h$  is also observed.

### 2.2. Density peaking

The effect of density peaking is found to result from the natural non asymmetry between species, because of collisions, adiabaticity of passing electrons or finite Larmor radius effects. Here, we keep  $L_p$  constant, and we vary  $L_n$  and  $L_T$ . We simplify the problem by removing the effect of collisions, and we take equal temperatures for ions and electrons. The result for  $n_e = 1.2 \times 10^{20}$  m<sup>-3</sup>,  $T_e = T_i = 1.6$  keV,  $r/a = 0.5$ ,  $q = 1.5$ ,  $s = 0.4$ ,  $R/L_p = 14$ , is shown in Figure 1 (right). We observe that low as well as high wavenumber modes are stabilized by short density scales. This stabilization is accompanied by a decrease of the diffusion coefficient  $D_h$ .

### 2.3. Magnetic shear

Drift waves are sensitive to the magnetic shear through the precession drift of trapped particle, but also through the toroidal coupling and parallel dynamics of passing ions. In our

model, we find that trapped particle contribution to the growth rate vanishes for  $s < -3/8$ , and that passing ions are stable around  $s = 0$ , because the distance ( $d$ ) between resonant surfaces is very large. In Figure 2, we present a contour plot of  $\gamma_n \lambda_n^2$  as function of the magnetic shear and of the toroidal wavenumber. Plasma parameters are :  $n_e = 10^{20} \text{ m}^{-3}$ ,  $T_e = T_i = 1.6 \text{ keV}$ ,  $q = 1.5$ ,  $r/a = 0.5$ ,  $R/L_p = 14$ ,  $R/L_n = 7$ , and the effect of collisions is removed.

A ionic branch is observed for strongly negative magnetic shear : it is the so-called parallel sound mode (or slab ion mode). The region  $s \approx -0.5$  corresponds to the most stable domain for curvature driven modes. We observe also that the spectrum is cancelled at high toroidal numbers by a strong magnetic shear, through radial localization effect.

### 3. Tore Supra PEP mode

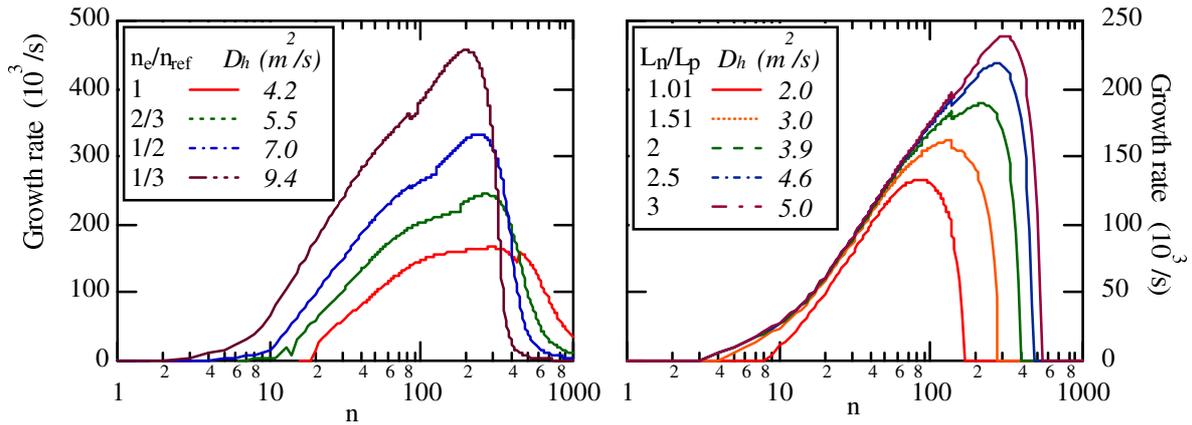
We consider the Tore Supra PEP mode 13656, and we compare the diffusion coefficient  $D_h$  during and after the improved confinement. The discretization is such that  $\Delta r = 0.02 \text{ m}$ . Collisional detrapping is implemented, and we have calculated  $D_h$  in PEP conditions for the following cases :

- **ExB** shear is ignored during PEP mode and the safety factor profile is taken equal to the post-PEP profile : this calculation outlines the role of density peaking and collisions ;
- **ExB** shear is implemented, but the safety factor is still unchanged between the two phases : **ExB** shear effect is outlined ;
- all effects are implemented, assuming that the current profile during PEP mode is the most hollow profile calculated with the magnetic equilibrium code IDENT-D.

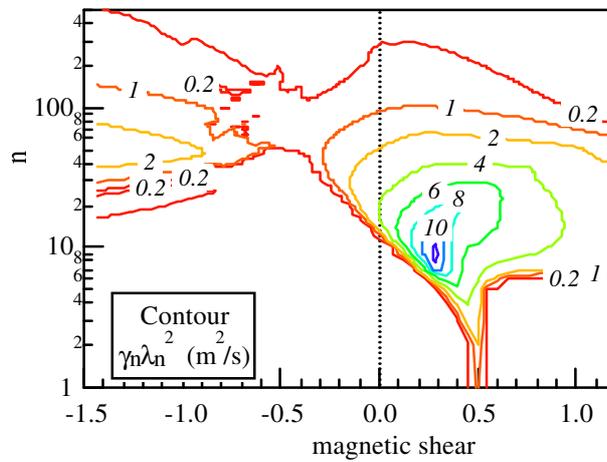
We compare these results to the complete calculation made in the post-PEP phase, as shown in Figure 3. The peaked density profile combined with **ExB** shear stabilization produces a strong reduction of  $D_h$  in the region of gradients (around  $r/a = 0.4$ ). In the case when a flat current profile is considered, two effects are involved : a better stabilization of drift waves modes, as shown in Figure 3, but also the elimination of most of the resonant surfaces at low wavenumbers for  $s \approx 0$ , which comes from  $N_{mn}$ , in our definition of  $D_h$ .

### 4. Conclusion

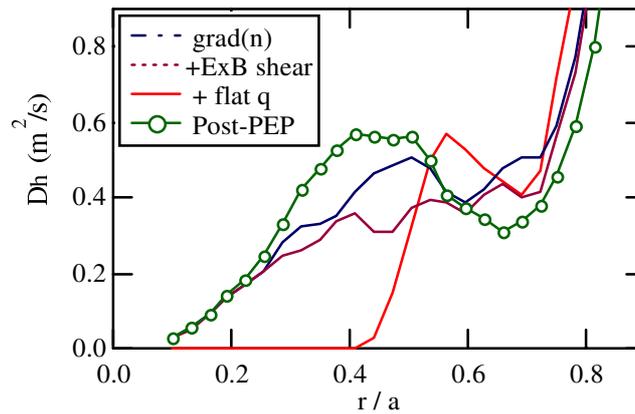
PEP mode in Tore Supra is found to involve three stabilizing mechanisms : density peaking, **ExB** shear, and low magnetic shear. It has to be stressed that a strong negative shear is not as favourable. The curvature driven modes are stable but a slab ITG branch appears, with significant growth rates. The most stable region for drift modes corresponds to  $s \approx -0.5$ . The low shear configuration is also favourable for the reason that it eliminates most of the resonant surfaces associated to low wavenumber modes, which imply a deep reduction of  $D_h$ . This analysis provides some keys to understand PEP modes in other devices, and clarifies in particular the respective importance of density peaking and magnetic shear in TFTR and JET.



**Figure 1.** Effect of collisional detrapping (left) and density peaking (right) on drift wave growth rate, as function of the toroidal wavenumber.



**Figure 2.** Contour plot of  $\gamma_n \lambda_n^2$ , as function of the magnetic shear and toroidal wavenumber.



**Figure 3.** Heuristic coefficient  $D_h$  for Tore Supra PEP mode 13656 : contribution of peaked density,  $E \times B$  shear and flat  $q$  profile are compared to the post-PEP profile.

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