Numerical investigation of a parallel shear flow instability in the tokamak edge

F. Schwander[1], G. Ciraolo[1], Ph. Ghendrih[2], E. Serre[1], P. Tamain[2]

[1]*M2P2 - UMR 6181, Ecole Centrale Marseille, IMT La Jetée, Tech. Château-Gombert, 38 rue Frédéric Joliot-Curie, 13451 Marseille Cedex 20, France.*

[2]*CEA, IRFM, 13108 Saint-Paul-lez-Durance, France.*

Introduction

Plasma-facing components in tokamaks locally alter plasma profiles, and can potentially alter transport in their vicinity. The case has been made that limiters can lead to plasma shear flow instabilities at the transition between the core and the Scrape-Off Layer (SOL) of a limiter plasma [1]. We investigate this possibility numerically in simulations of the edge region of the tokamak encompassing the core and the SOL, by studying the susceptibility of axisymmetric equilibria to the instability by consideration of a local instability parameter, and the linear growth of small amplitude, non-axisymetric pertubations.

Model equations

To this aim, we perform simulations of a fluid model of electrostatic turbulence, governed by the following conservation equations for the particle density n and for parallel momentum Γ, assuming that ions are cold, and have constant temperature across the cross-section:

$$\partial_t n + \nabla_\parallel \Gamma + \rho_* \varepsilon [\Phi, n] = D^* \nabla_\perp^2 n \quad (1)$$

$$\partial_t \Gamma + \nabla_\parallel \left(\frac{\Gamma^2}{n} + n \right) + \rho_* \varepsilon [\Phi, \Gamma] = \mu^* \nabla_\perp^2 \Gamma \quad (2)$$

where density and parallel momentum adimensionalized to reference values n_{ref} and $\Gamma_{\mathrm{ref}} = n_{\mathrm{ref}} c_s$, c_s being the ion sound speed. The spatial operators used have the following definitions:

$$\nabla_\parallel f = \mathbf{b} \cdot \nabla f \quad ; \quad [f, g] = \mathbf{b} \cdot (\nabla f \times \nabla g) \quad ; \quad \nabla_\perp^2 f = (\nabla^2 - \nabla_\parallel^2) f$$

where $\mathbf{b}$ is the unit vector along the magnetic field, with the parallel gradient and the perpendicular operators have adimenzionalized with the parallel connection length $L_\parallel$ and the minor radius a respectively, time adimensionalized to the parallel acoustic time $t_{\mathrm{ref}} = L_\parallel / c_s$. The electric potential Φ is adimensionalized to $\Phi_{\mathrm{ref}} = T_e / e$, and with the assumption that electrons are adiabatic is given by $\Phi = \ln(n / \langle n \rangle)$ where $\langle . \rangle$ denotes flux-surface averaging. This model accounts for the combined effects of parallel, nonlinear acoustic dynamics along magnetic field lines, perpendicular advection by the electric drift (Poisson brackets in the equations above), and perpendicular diffusion by background micro-turbulence which we assume has weak coupling with the instability under study. The system is then governed by the dimensionless parameters:

$$\varepsilon = L_{\parallel}/a \qquad ; \qquad \rho_{*} = T_e/(eB_0 c_s); \tag{3}$$

$$D^{*} = DL_{\parallel}/(c_s a^2) \qquad ; \qquad \mu^{*} = \mu L_{\parallel}/(c_s a^2) \tag{4}$$

where D and μ correspond to effective particle and momentum diffusivities respectively.

This model allows firstly to compute reasonable profiles in the core/SOL region while also giving rise to the parallel shear flow instability (which is the only instability in the system in the absence of curvature and with assumptions above).

Overview on the parallel shear flow instability

Assuming only radially varying equilibrium profiles, the parallel shear flow instability is generally expected to grow whenever destabilization by the radial Mach number gradient exceeds stabilization by the density gradient, i.e. when:

$$\left|\frac{\mathrm{d}M_0}{\mathrm{d}r}\right|^2 - \left|\frac{\mathrm{d}\ln n_0}{\mathrm{d}r}\right|^2 > 0 \tag{5}$$

Including the effect of perpendicular transport, the instability threshold can be reached more easily [3] because of the presence of an additional, systematically destabilizing contribution of the parallel momentum gradient in the instability criterion given below:

$$\gamma = \left|\frac{\mathrm{d}M_0}{\mathrm{d}r}\right|^2 - \left|\frac{\mathrm{d}\ln n_0}{\mathrm{d}r}\right|^2 + \frac{[\delta^{1/2} - \delta^{-1/2}]^2}{4}\left|\frac{1}{n_0}\frac{\mathrm{d}\Gamma_0}{\mathrm{d}r}\right|^2 > 0 \tag{6}$$

where $\delta = \mu^{*}/D^{*}$ is the diffusivity ratio.

Diagnostic of equilibria

We obtain steady, axisymmetric solutions of the model Equations 1 and 2 in the outer edge of a tokamak with circular cross-section, with a limiter at the bottom of the cross-section. The parallel Mach number is imposed on the inner radial boundary so as to mimic core rotation, and perpendicular diffusion coefficients are given differing values in order to slightly favour the instability, with $D^{*} = 3\times10^{-2}$ and $\mu^{*} = 3\times10^{-3}$. Profiles obtained for core Mach number of 0.5 are shown in Figure 1. The core plasma flows from left to right, and sheath acceleration produces a parallel momentum shear layer in the neighbourhood of the core/SOL transition. The largest shear is naturally located on the side of the limiter where the scrape-off and core flows are in opposite direction, downstream of the limiter relative to the core rotation. n the model considered, the instability parameter γ (given in Equation 6) is maximum, and non-axisymmetric, unstable fluctations effectively grow at this location.

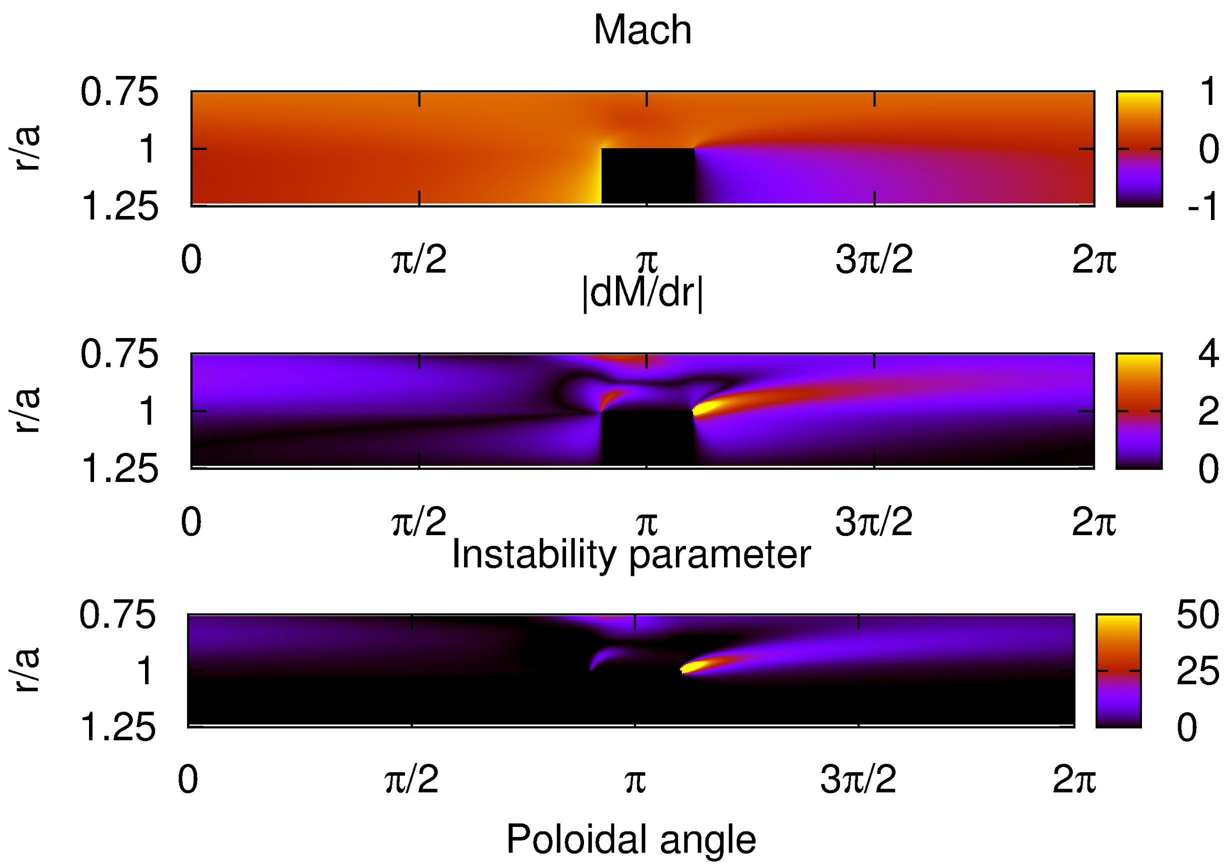

Figure 1: Spatial distribution of the parallel Mach number(top), Mach number gradient (middle), and instability parameter (bottom).

Effect of core rotation

Core parallel flows can occur as a result of different mechanisms (NBI heating, ripple losses, intrinsic rotation), and reach significant rotations rates. Since the mechanism leading to the parallel shear flow is the momentum shear between the core and the scrape-off layer, where the Mach number goes from ± 1 to about zero with zero rotation, core rotation can enhance the instability on the side of the limiter where sheath acceleration forces the flow in the direction opposite to core rotation. Axisymmetric profiles show little qualitative difference depending on core Mach number, and profiles obtained for core Mach number of 0.375 and 0.250 are very similar to those obtained for Mach=0.500 shown in Figure 1. Instability properties are however markedly changed: based on the obtained equilibrium solutions, we study the growth of small amplitude pertubations with prescribed toroidal wavenumber. The corresponding linear growth rates for 3 values of Mach are shown in Figure 2. These growth rates show a nearly parabolic dependence on toroidal wavenumber, as expected from a WKB analysis of the parallel shear flow instability, and highlight the influence of core rotation: unstable fluctuations have toroidal wavenumber up to 20 and maximum growth rate of 1.18 for the fastest rotation considered,

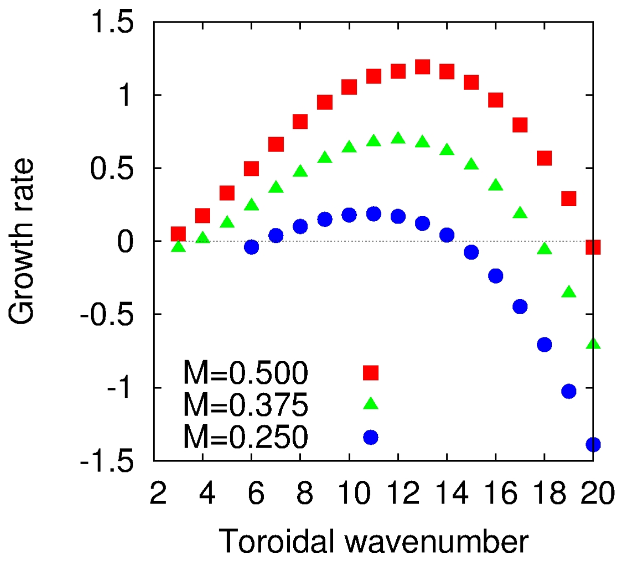

Figure 2: Global linear growth rates of non-axisymmetric fluctuations as a function of toroidal wavenumber for core Mach number of 0.250, 0.375 and 0.500.

instead of 14 and 0.15 respectvely for the slower rotation.

Discussion

We have investigated the parallel shear flow instability in the edge of a limiter plasma, by giving profiles of a local instability parameter in an isothermal plasma with adiabatic electrons. The maximum values of the latter maximum coincide with a Mach number shear layer close to the core/SOL transition, downstream of a limiter when the core plasma rotates with non-negligible Mach number. Investigation of the growth rates of non-axisymmetric fluctuations shows that core rotation has a significant impact on their linear growth rates, and that fast core rotation favours the parallel shear flow instability in the vicinity of a limiter.

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