Plasma flow in tokamaks: unraveling the competition and synergy between turbulence and 3D magnetic perturbations

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The present study addresses the complex issue of flow control in tokamak plasmas. Flow shaping in large size magnetized plasmas is not easily achievable with external momentum sources. Flows are rather determined by intrinsic physics that combine competing turbulent and collisonal effects in presence of 3D magnetic perturbations. Turbulence can indeed drive the mean plasma toroidal velocity V_T through wave-particle interactions that provide a finite momentum to the plasma. More generally, the dynamic effects induced by turbulence can be included in the toroidal Reynolds stress Π that can be written as a sum of a viscous, pinch and residual terms:

$$\Pi = -\chi \partial_r V_T + \mathscr{V} V_T + \Pi_{res} \tag{1}$$

Where χ is the turbulent viscosity, $\mathscr{V}$ is a pinch coefficient and Π_{res} is the residual stress. The latter is the source term accounting for the wave-particle interactions and that drive the intrinsic rotation of the plasma in absence of 3D magnetic perturbation. This turbulent drive is well documented [1, 2, 3, 4]. The impact of 3D magnetic perturbation on spontaneous rotation is of a different nature. Such a perturbation constrains particle trajectories with toroidal and poloidal trappings. The resonant enhancement of collisional processes of these trapped populations is responsible for a macroscopic effect on flows, and constitutes the so-called neoclassical theory. One can then shows that 3D magnetic perturbation leads to magnetic braking $\mathscr{M}$, i.e. a thermal force that sets the mean toroidal velocity toward a finite value V_{neo}. It can be expressed:

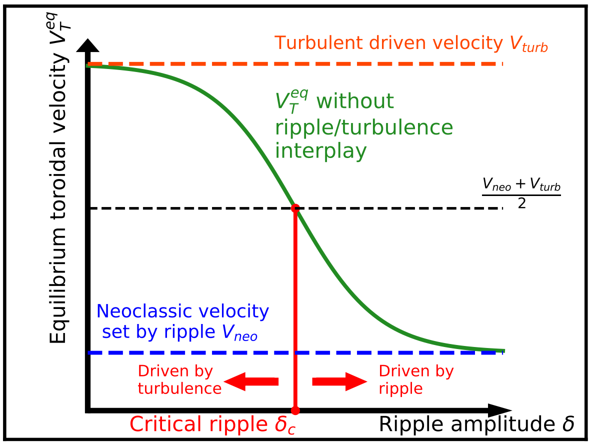

Figure 1: *Sketch of the modelled ripple/turbulence competition on the equilibrium toroidal velocity.*

$$\mathscr{M} = -\nu_\varphi (V_T - V_{neo}) \tag{2}$$

with ν_φ the neoclassical friction that sets at which rate the plasma velocity reaches V_{neo}. Usually turbulent drive and 3D magnetic perturbation are handled separately in numerical simulations.

In this work [5], they are treated on an equal footing, which allows addressing the competition and also possible synergies for the first time. To this aim, both analytical theory and gyrokinetic simulations with the GYSELA code [6] are used. From Eq.1 and Eq.2, the analytical model simply reads:

$$\partial_t V_T = \mathscr{M} - r^{-1}(r\Pi)' \qquad (3)$$

where r is the radial coordinate and $'$ stands for the radial derivative. It leads to an expression for the equilibrium velocity:

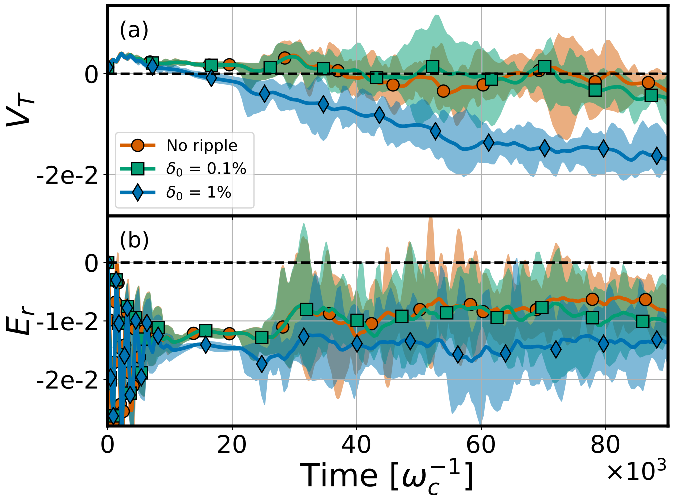

Figure 2: *Time trace of the toroidal velocity V_T (a) and the radial electric field E_r (b) in $0.45 < r/a < 0.55$ (shaded areas, mean: solid lines) for different ripple amplitudes.*

$$V_{Teq} = \frac{\nu_\varphi V_{neo} - r^{-1}(r\Pi_{res})'}{\nu_\varphi + \chi\lambda_v + \mathscr{V}\kappa_v} \qquad (4)$$

with $\lambda_v = -(r\chi V'_{Teq})'/(r\chi V_{Teq})$ and $\kappa_v = (r\mathscr{V}V_{Teq})'/(r\mathscr{V}V_{Teq})$. As the neoclassical friction ν_φ is monotonous with the amplitude δ of the 3D magnetic perturbation, it appears that $\delta \to 0 \Rightarrow V_{Teq} \to V_{turb} = -\frac{r^{-1}(r\Pi_{res})'}{\chi\lambda_v + \mathscr{V}\kappa_v}$ and $\delta \to \infty \Rightarrow V_{Teq} \to V_{neo}$. As displayed in Fig.1, one can define a critical amplitude δ_c of the perturbation such that $V_{Teq}(\delta_c) = (V_{neo} + V_{turb})/2$. Above this threshold, the plasma velocity is then closer to its neoclassical prediction than its turbulent one. This value is then convenient to know the main drive of the intrinsic rotation. The interesting feature of this quantity is that it only depends on the damping rates and not the sources terms, i.e. $\nu_\varphi(\delta_c) = |\lambda_v|\chi_{eff}$ with the effective viscosity defined as $\chi_{eff} = \chi + (\kappa_v/\lambda_v)\mathscr{V}$. A consequent numerical effort has been performed in order to validate this model. The considered magnetic perturbation is a poloidally symmetric magnetic ripple with a radial gaussian envelope centered at mid radius: $\delta(r) = \delta_0 e^{-32(r/a-0.5)^2}$ with an arbitrary δ_0 and a the minor radius. Using the gyrokinetic code GYSELA, the methodology consists in three steps. First, simulations with only neoclassical contribution and including ripple have been successfully compared to the neoclassical theory [7, 8] (in particular the neoclassical friction ν_φ). Secondly, in simulations of Ion Temperature Gradient driven turbulence without ripple, turbulent momentum transport have been analyzed and compared with available models of turbulent transport [5, 1, 2]. The viscosity profile χ of the simulated has then been retrieved and the pinch $\mathscr{V}$ found negligible. Finally, all effects are self-consistently accounted for to assess the resulting flow. With the GYSELA results on v_φ and χ, the critical ripple for the simulated turbulence is estimated at $\delta_c \sim 0.55\%$. Two other simulations with $\delta \ll \delta_c$ and $\delta \gg \delta_c$ then shows that only the latter case is strongly driven by the magnetic braking, i.e. Fig.2. As displayed, the magnetic braking also influences the radial electric field which is of prime importance for accessibility to improved confinement modes. The order of magnitude of the critical amplitude can be obtained with some approximations. First, $\kappa_v/$ and λ_v look quite complex to obtain in practice, but can be approximated according that χ, $\mathscr{V}$ and V_T follows the characteristic length scale of the equilibrium gradients. Using here the temperature gradient length L_T as a proxy, one can estimate $\lambda_v \sim L_T^{-1}$ and $\kappa_v \sim L_T^{-2}$.

Secondly, the so-called *ripple-plateau* scaling for the neoclassical friction, i.e. $\nu_\varphi \sim (N_c V_{th}/R)\delta^2$ (with V_{th} the thermal velocity), is relevant for most tokamaks. Finally, the gyroBohm scaling for the effective turbulent viscosity, i.e. $\chi_{eff} \sim V_{th}\rho_i^2/L_T$ (with ρ_i the Larmor radius), can be considered. A rule-of-thumb can then be written for the critical ripple amplitude:

$$\delta_c \sim \sqrt{N_c}\frac{\rho_i}{R}\left(\frac{R}{L_T}\right)^{-3/2} \qquad (5)$$

Moreover, interplay mechanisms between magnetic braking and turbulent momentum drive are here addressed. This study is restrained to non-resonant 3D magnetic perturbation. With this constraint, it is clear that the impact of turbulence on the magnetic braking is negligible as the only mechanism of synergy is through mode-coupling on the electric potential. However, the impact of magnetic braking on the turbulent drive is found to be significant. As theoretical predictions showed that the toroidal Reynolds stress depends on the shear of turbulent intensity $\mathscr{I}'$ [9] and the shear of radial electric field E_r' [10]. Both of these quantities are expected to be impacted by 3D magnetic perturbations. Indeed, the mode-

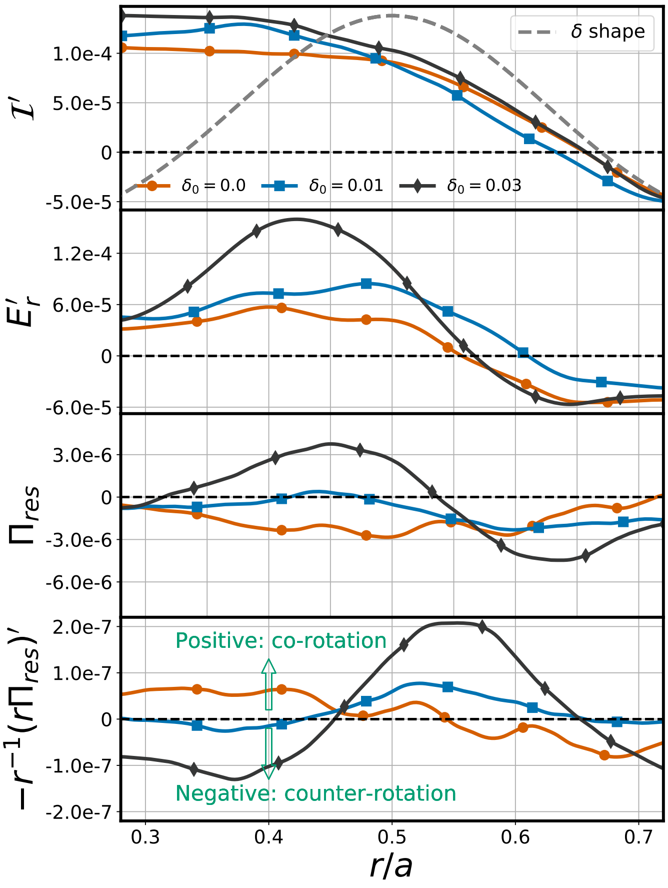

Figure 3: *Radial profiles of turbulent intensity shear, E_r shear, residual stress and its divergence. These profiles are coarse-grained as detailed in [5].*

coupling on the electric potential of resonant modes with the "neoclassical" modes coming from the magnetic perturbation can modify the turbulent spectra, i.e. the turbulent intensity $\mathscr{I}$. In addition, as seen in Fig.2, the neoclassical processes modify the radial electric field E_r. However, quantifying these impacts analytically is out of the scope of this study that rather make use of gyrokinetic simulations. Once again, a radially gaussian magnetic ripple is considered as the 3D magnetic perturbation. The simulations have been performed with a flat profile of toroidal velocity so the toroidal Reynolds stress is dominated by the residual stress Π_{res}. The profiles of I', E_r', Π_{res} and $r^{-1}(r\Pi_{res})'$ are plotted in Fig.3. It is found that the modification of I' by ripple is mild and not correlated with the change on the residual stress. However, the modification of E_r' by ripple is clearly correlated with the one observed on Π_{res}. The effect is significant in our simulations, as the source term $r^{-1}(r\Pi_{res})'$ even changes sign in presence of magnetic ripple. This work can be of use to strengthen the predictions on flows and E_r for real experiments where these quantities play a major role for the plasma performances.

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