Turbulence stabilisation by parallel flows for the DIII-D shortfall case

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This paper explores the combined impact of toroidal flow u, parallel flow shear $u'_{\parallel}$ and perpendicular flow shear γ_E on turbulent transport. The study started in the frame of a multi-code benchmark effort based on the DIII-D L-mode shortfall case [1] and was motivated by the unexpectedly strong impact of the toroidal flow on the non-linear heat fluxes observed with the gyrokinetic code GKW [2]. The simulations presented here are performed for the experimental parameters of the DIII-D shortfall case at $r/a = 0.8$ with the electron temperature gradient set to zero, which corresponds to the benchmark case focusing on ion-scale turbulence. Pure toroidal rotation was assumed to compute the $E \times B$ and parallel flow shear from the measured toroidal rotation profile. The corresponding input parameters, given in Table 1, are typical of the edge of an L-mode plasma with moderate NBI heating. In Table 1, the toroidal flow $u = R_0\omega_\varphi/v_{\rm thi}$ and flow shear $u' = -R_0^2/v_{\rm thi}\partial\omega_\varphi/\partial r$ are normalised to the ion thermal velocity $v_{\rm thi} = \sqrt{2T_i/m_i}$ and R_0 is a reference major radius. Electromagnetic perturbations (ϕ and $A_{\parallel}$), kinetic electrons and

R/L_{Ti}	R/L_{Te}	T_e/T_i	R/L_n	u	u'	γ_E	$\nu_{\rm eff}$	$Z_{\rm eff}$	β	ε	q	$\hat{s}$
7	0	0.85	3	-0.15	-1.25	-0.2	1.45	1.33	8.10^{-4}	0.28	2.8	2.05

Table 1: *Reference input parameters based on the DIII-D shortfall case at $r/a = 0.8$ and given here in GKW normalised units (see [2] for details on the normalising conventions).*

collisonal pitch-angle scattering are included in the simulations performed with the flux-tube version of GKW. The magnetic equilibrium is specified using the Miller parametrisation.

The destabilising effect of the parallel flow shear $u'_{\parallel}$ and the stabilising effect of the toroidal flow u on the toroidal ITG are well known and have been explored in several studies. Their combined effect, however, has been left mostly unexplored. To tackle this point, a simple dispersion relation emphasising the respective contributions of u and $u'_{\parallel}$ on the linear growth rate is first presented before moving to the numerical results obtained with GKW.

Following Ref. 3, a 1-point (low field side midplane) fluid model is built from the first three moments of the linearised gyrokinetic equation in the local δf approximation. The electron response is considered to be adiabatic and finite Larmor radius effects are neglected. In the limit of marginally unstable modes ($\gamma > 0$ and $\gamma \ll \omega_R$ with γ the mode growth rate and ω_R the mode frequency, respectively) and of small parallel symmetry breaking ($u+k_{\|N} \ll 1$ with $k_{\|N}$ a normalised parallel wave vector), a simple dispersion relation is obtained. This dispersion relation describes the toroidal ITG including flows effects. For $R/L_n = 0$, it leads to the following growth rate:

$$\gamma = k_\theta \rho_i \frac{v_{\rm thi}}{R_0} \sqrt{2R/L_{Ti} - \frac{49}{3} + 12(u+k_{\|N})u'_{\|} - 52(u+k_{\|N})^2} \quad (1)$$

This equation is readily obtained starting from Eq. (13) and (16) of Ref. 3 in which the details of the derivation of the fluid model and the normalisations are outlined. Eq. (1) indicates that the mode growth rate depends on the parallel mode structure via the term $k_{\|N}$. Owing to the simplicity of the model, a meaningful value of $k_{\|N}$ cannot be determined self-consistently: it would at least require to relax the 1-point approximation and the adiabatic electrons assumption. Representative values can nevetheless be assessed from gyrokinetic simulations allowing a qualitative discussion while keeping the model as simple as possible. Toroidal flow and parallel flow shear are known to break the parallel symmetry of the gyrokinetic equation and to generate finite values of $k_{\|N}$. This resulting $k_{\|N}$ is mostly proportional to u and $u'_{\|}$, with a slope of opposite sign, as shown in Fig. 3 of Ref. 4. Taking this scaling into account, Eq. (1) can be rewritten as:

$$\gamma = k_\theta \rho_i \frac{v_{\rm thi}}{R_0} \sqrt{2R/L_{Ti} - \frac{49}{3} + a{u'_{\|}}^2 - buu'_{\|} - cu^2} \quad (2)$$

which emphasizes the quadratic dependence of the mode growth rate on u and $u'_{\|}$. The coefficients a and b are usually positive and c is always positive. At $u = 0$, the destabilising effect of the parallel flow shear is recovered, as is the stabilising effect of toroidal rotation at $u'_{\|} = 0$. At finite u and $u'_{\|}$ anything can happen, with u and $u'_{\|}$ having a stabilising or destabilising effect depending on their respective values. This qualitative picture is confirmed in linear gyrokinetic

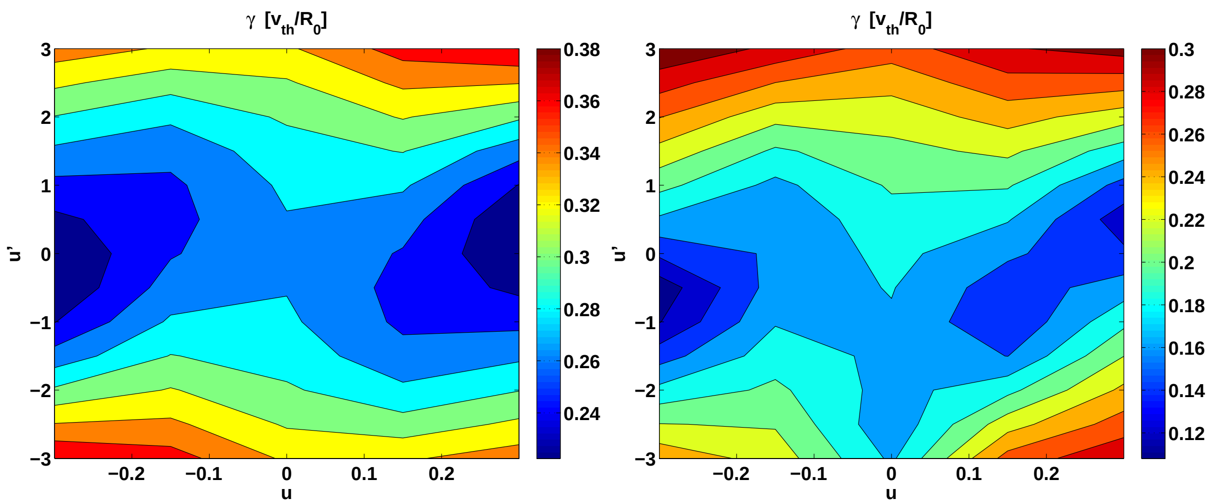

Figure 1: *Linear mode growth rate as a function of the toroidal rotation u and parallel flow shear* $u'_{\|}$ *at* $k_\theta \rho_i = 0.4$ *for* $k_r \rho_i = 0$ *(left plot) and* $k_r \rho_i = 0.2$ *(right plot).*

simulations for the reference case at $k_\theta \rho_i = 0.4$ (close to the most unstable mode), as shown in Fig. 1a. Running the same simulations for a finite radial wavevector $k_r \rho_i = 0.2$ shows an overall decrease of the mode growth rate, as expected, but also a significant modification of the u and $u'_\parallel$ dependencies, Fig. 1b. This is understood considering that a finite radial wavevector shifts the maximum of the electrostatic potential away from the low field side midplane with a corresponding contribution to $k_{\parallel N}$ independent of u and $u'_\parallel$ and a subsequent modification of Eq. (2).

To investigate how the dependencies of the mode growth rate on u and $u'_\parallel$ affect the non-linear heat fluxes, non-linear simulations are performed for the reference case varying the flow parameters around their nominal values. The perpendicular dynamics is described in Fourier space with 21 poloidal wavevectors ($k_\theta \rho_i = 0$ to 1.36) and 339 radial wavevectors ($k_r \rho_i = -24.2$ to 24.2). Finite differences are used in the parallel direction with 32 points along the field line. The velocity space is discretized with 16 μ points and 64 $v_\parallel$ points. The simulations are run until a converged time average of the heat fluxes is obtained, which depending on the simulations requires between 400 to 900 R_0/v_{thi} after the non-linear overshoot. In Fig. 2a, the non-linear

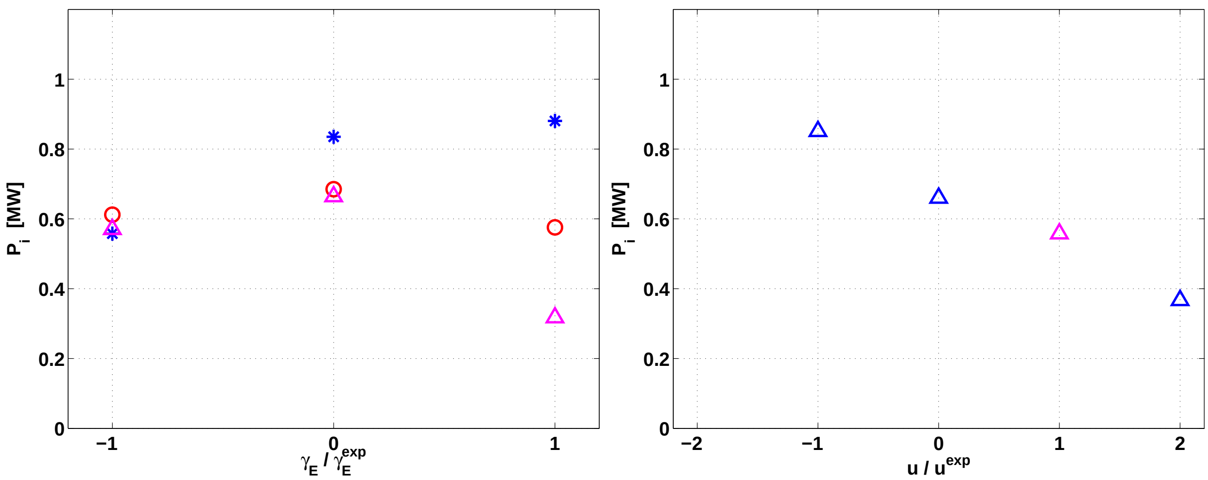

Figure 2: *Left plot: non-linear radial ion heat flux ($P_i = Q_i V'$, with V the flux surface volume) as a function of the $E \times B$ shearing rate γ_E for $u'_\parallel = u'_{\parallel exp}$ (blue stars), $u' = 0$ (red circles) and $u' = -u'_{exp}$ (magenta triangles). Right plot: P_i as a function of the toroidal rotation u for the case $\gamma_E = -\gamma_E^{exp}$ and $u'_\parallel = -u'_{\parallel exp}$.*

ion heat flux obtained in these simulations is shown as a function of the $E \times B$ shearing rate for different values of the parallel flow shear. The toroidal rotation is kept at the nominal value: $u = u^{\mathrm{exp}}$. For $u'_\parallel = 0$ (red circles), the ion heat flux is maximum at $\gamma_E = 0$ and decreases at finite γ_E, irrespectively of its sign, in agreement with the conventional picture. In contrast, at finite parallel flow shear, $u'_\parallel = \pm u'_{\parallel \mathrm{exp}}$, the ion heat flux is no longer symmetric with respect to

$\gamma_E = 0$ and the heat flux reduction depends on the respective signs of $u'_{\parallel}$ and γ_E. At $u'_{\parallel} = u'_{\parallel\text{exp}}$, an increase of the $E \times B$ shearing rate from zero to its nominal value even results in a slight increase of the ion heat flux. Quantitatively, the heat flux reduction obtained when simply changing the sign of the flow and flow shear parameters can be very large: at $\gamma_E = \gamma_E^{\text{exp}}$, changing the sign of $u'_{\parallel}$ results in a reduction by a factor of almost 3 of the ion heat flux. A similar behavior is observed for the electron heat flux. In Fig. 2a, the different dependency on $u'_{\parallel}$ obtained at positive or negative γ_E is induced by the finite toroidal rotation. To highlight this point, the ion heat flux is shown in Fig. 2b as a function of the toroidal rotation u for the case with $u'_{\parallel} = -u'_{\parallel\text{exp}}$ and $\gamma_E = -\gamma_E^{\text{exp}}$. An almost linear dependence of the ion heat flux on the toroidal rotation is observed with an increase by about 50% when the direction of the toroidal flow is reversed. These results are qualitatively consistent with the linear picture: the strongest reduction of the linear growth rate and non-linear ion heat flux are obtained when the flow parameters conjugate to generate a large parallel symmetry breaking. The effect obtained in the non-linear simulations is however somewhat stronger than what one would expect from the linear stability analysis.

Turning now to the relevance of this mechanism in the experiments, there are a two main points to be made. The first one is that the DIII-D shortfall case is an L-mode plasma with moderate NBI injection and therefore rather modest flow values. Scaling up the flow parameters, an effect even stronger than what is observed in Fig. 2 would be expected from the linear stability results. The second point concerns the possibility to experimentally decouple the flow parameters. The decoupling of $u'_{\parallel}$ and γ_E depends directly on the poloidal rotation and pressure gradient. In the limit of zero poloidal rotation and pressure gradient, $u'_{\parallel}$ and γ_E are strictly coupled. It is only when the radial electric field is mostly carried by the poloidal rotation or the pressure gradient that γ_E can assume values not proportional to $u'_{\parallel}$. This is typically the case in transport barriers. The decoupling of u from $u'_{\parallel}$ and γ_E is, to some extent, easier to achieve provided the toroidal rotation is driven by NBI and that one has a knob to change the edge toroidal rotation (magnetic perturbations and/or X-point radial position for instance).

References

[1] C. Holland *et al.*, Phys. Plasmas **16**, 052301 (2009)
`https://fusion.gat.com/theory/Shortfall`

[2] A.G. Peeters *et al.*, Comput. Phys. Commun. **180**, 2650 (2009).

[3] A.G. Peeters *et al.*, Phys. Plasmas **16**, 062311 (2009)

[4] Y. Camenen *et al.*, Phys. Plasmas **16**, 012503 (2009)