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Zonal Flow Amplification in Rotating Tokamak Plasmas

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ABSTRACT

- Gyrokinetic ITG turbulence simulations show that an equilibrium parallel rotation shear $U'_{\parallel,eq}$ amplifies the zonal flow and lowers the turbulence level in the saturated state.
- A potential vorticity (PV) transport analysis elucidates the physics mechanism behind this observation.
- With $U'_{\parallel,eq}$, a larger PV flux with a coherent radial structure is driven at the onset time of a zonal flow. The PV convection by the zonal flow induces a PV flux whose radial structure is aligned with the initial coherent zonal flow structure, promoting a positive feedback between the zonal flow and turbulence.
- Without $U'_{\parallel,eq}$, the radial profile of the zonal-flow induced flux is inconsistent with that of the zonal flow at the zonal flow onset time, hindering the positive feedback.

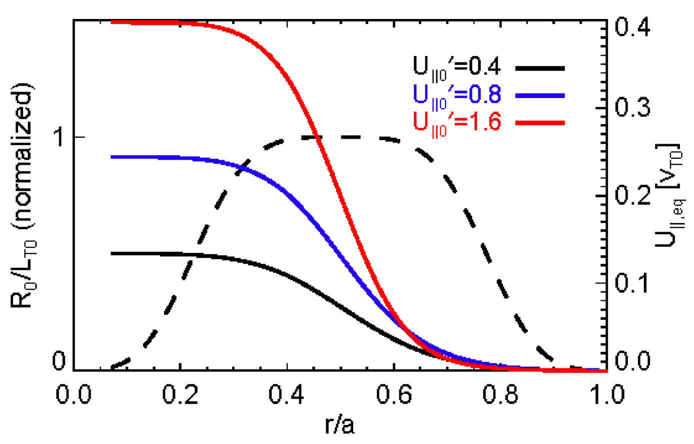
BACKGROUND

- Many tokamak experiments have demonstrated improved core confinement with high toroidal rotation shear $U'_{\parallel,eq}$ [*M. W. Shafer et al 2009, P. Mantica et al 2009*].
- A conventional approach based on the competition between two conflicting effects of $U'_{\parallel,eq}$: It can destabilize linear instabilities [*J. Q. Dong and W. Horton 1993*] and/or enhance the E × B shear stabilization [*K.H. Burrell et al 1997*]. However, this conventional picture is insufficient to explain the impact of the rotation on transport.
- Turbulence-driven zonal flows (ZFs) are a plausible physics mechanism. A gyrokinetic simulation study manifests an essential role of the parallel compression in ZF generation [*S. Yi et al 2019*]. Because parallel velocity fluctuation and thus its parallel compression are expected to increase with $U'_{\parallel,eq}$, zonal flow generation in rotating plasmas can impact on their confinement.

METHODS

Gyrokinetic simulations of toroidal ITG turbulence

- A global δf particle-in-cell code, the gKPSP code [*J.-M. Kwon et al 2012, 2017*]
- Adiabatic electron response
- Scans of $U'_{\parallel 0} \equiv -(a/v_{T0}) dU_{\parallel,eq}(r_c)/dr$ with R_0/L_{T_0}=5.2
- Except for the equilibrium sheared rotation and the $T_{i,eq}$ gradient, other plasma parameters are very similar to the CYCLONE base case.



equilibrium profiles of ion temperature gradient (broken) and parallel rotation (solid)

Analysis of potential vorticity (PV) transport

ZF generation can be described by the flux of PV:

$$\frac{\partial V_{ZF}}{\partial t} = \langle \frac{\omega_{ci0}}{n_{i,eq}} \int dv \delta F_i \left(c \frac{\hat{\varphi} \times \nabla_\perp J_0 \delta\phi}{B_0} \right)_r \rangle \equiv \Gamma_\Omega.$$

In terms of the fluid moments of δF_i,

$$\Gamma_\Omega \approx \omega_{ci0} \langle \left(\frac{c}{B_0} \hat{\varphi} \times \nabla_\perp \delta\phi \right)_r \frac{\delta N}{n_{i,eq}} \rangle + \omega_{ci0} \langle \left(\frac{c}{B_0} \hat{\varphi} \times \nabla_\perp \frac{\nabla_\perp^2 \delta\phi}{\omega_{ci}^2} \right)_r \frac{\delta P_\perp}{2 m_i n_{i,eq}} \rangle .$$

The gyro-center density δN acts as an effective PV. Then, the contributions of the δN evolution mechanisms on the net PV flux Γ_X can be evaluated as follows:

$$\Gamma_\Omega = \Gamma_\parallel + \Gamma_B + \Gamma_{E\times B} + \Gamma_{\langle\delta\phi\rangle} + \Gamma_{NL} + \Gamma_{FLR},$$

$$\Gamma_X \equiv \omega_{ci0} \langle \left(\frac{c}{B_0} \hat{\varphi} \times \nabla_\perp \delta\phi \right)_r \frac{\delta N_X}{n_{i,eq}} \rangle,$$

$$\delta N_X \equiv \int dt \left. \frac{\partial \delta N}{\partial t} \right|_X,$$

$$\frac{\partial \delta N}{\partial t} = \left. \frac{\partial \delta N}{\partial t} \right|_\parallel + \left. \frac{\partial \delta N}{\partial t} \right|_B + \left. \frac{\partial \delta N}{\partial t} \right|_{E\times B} + \left. \frac{\partial \delta N}{\partial t} \right|_{\langle\delta\phi\rangle} + \left. \frac{\partial \delta N}{\partial t} \right|_{NL}.$$

Here the all $\partial \delta N / \partial t|_X$ are evaluated term by term.

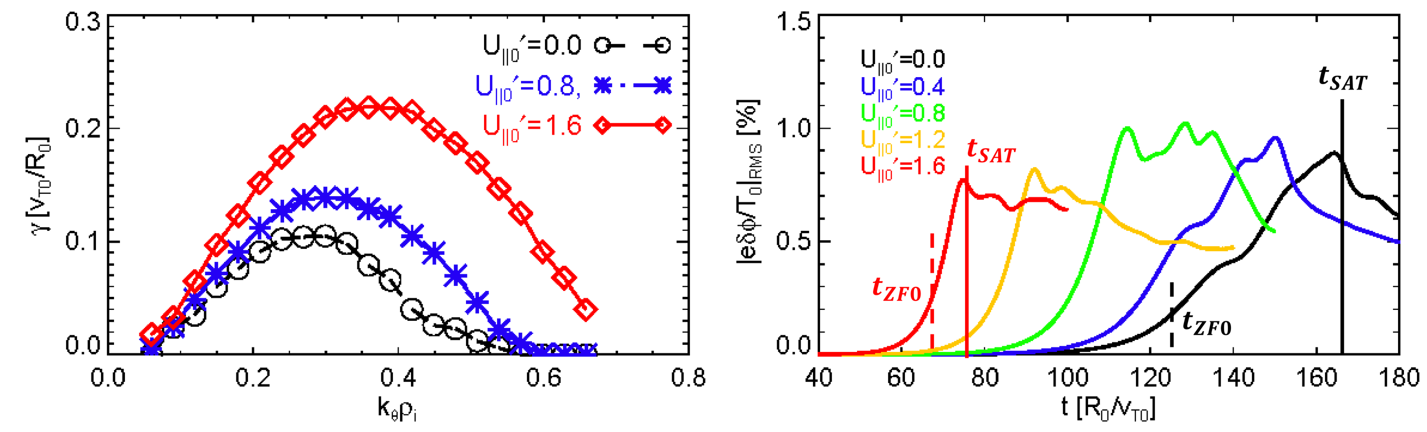
CONCLUSION

- A PV transport analysis uncovers that the positive feedback between turbulence and ZF is enhanced with $U'_{\parallel 0}$ and results in the decreased turbulence saturation level, observed in gyrokinetic simulations.
- The self-organization processes in static plasmas show a more complicated behavior. This requires further simulation and theory studies.

OUTCOME

Turbulence saturation levels for different $U'_{\parallel 0}$

In spite of the continuous increase in the linear instability with $U'_{\parallel 0}$, the turbulence levels decrease with a strong $U'_{\parallel 0} \geq 1.2$.



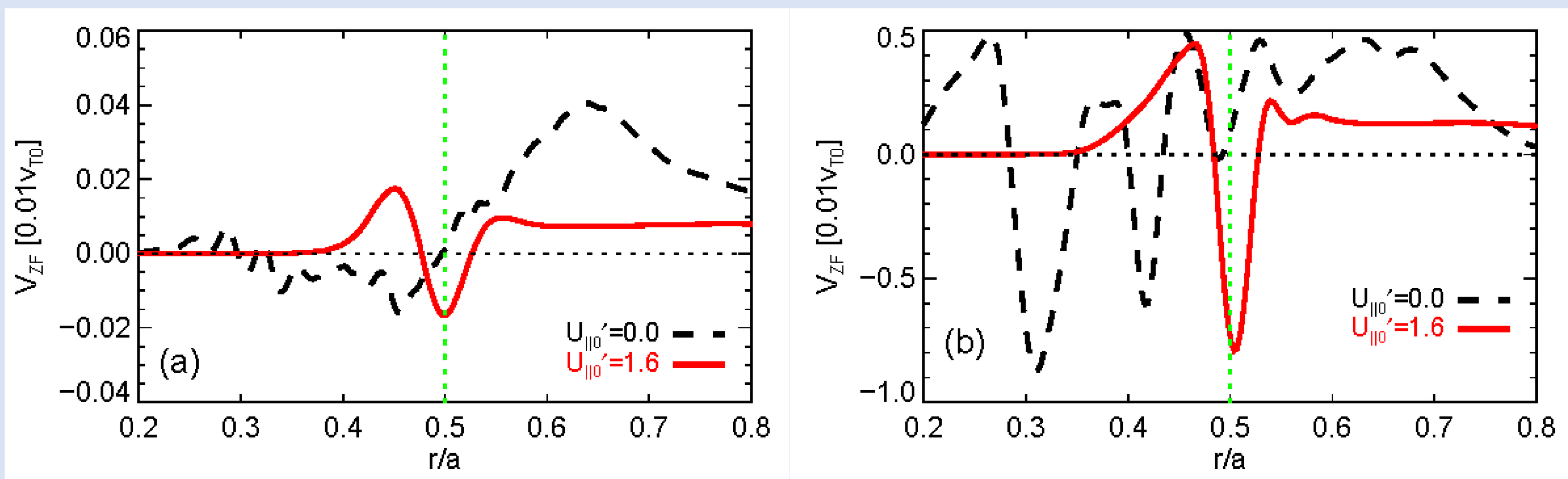
Linear growth rate as a function of $k_\theta \rho_i$ (left) and time histories of the potential fluctuation amplitudes (right) for different $U'_{\parallel 0}$ with $R_0/L_{T0} = 5.2$.

Efficient zonal flow generation with $U'_{\parallel 0}$

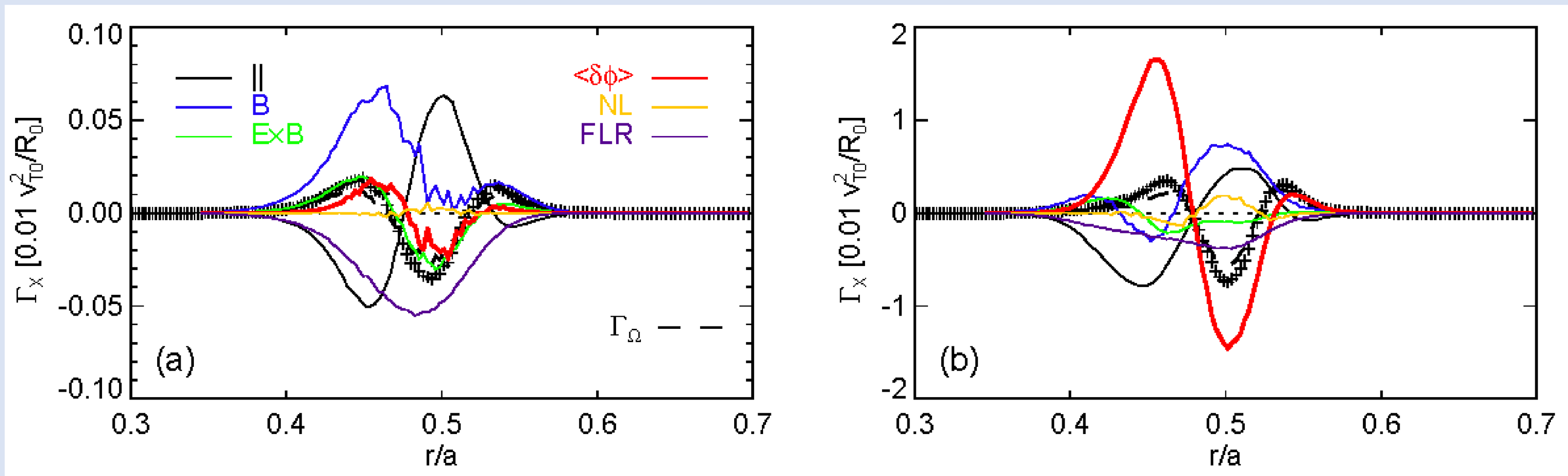
- With $U'_{\parallel 0}$, an initially driven short-radial scale ZF keep its radial structure constant during the whole build-up phase. The ZF is efficiently amplified during a short time interval. The strong ZF shear leads turbulence growth to be quenched at the lower saturation level.
- Without $U'_{\parallel 0}$, a ZF with a broad radial profile is initially driven. The ZF radial profile changes in time during its build-up time. The development of the ZF is a long time after its onset. This allows turbulence to reach to a higher level.

Enhanced positive feedback between turbulence and zonal flow

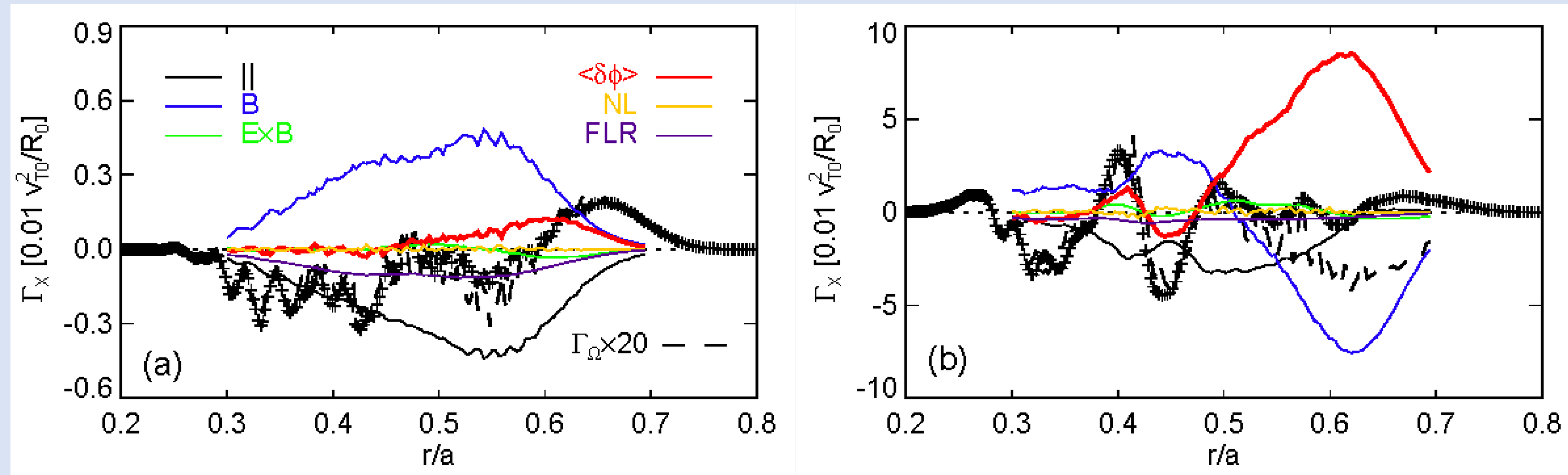
- In the presence of $U'_{\parallel 0}$,
  - ✓ the enhanced imbalance among Γ_X drives much larger Γ_Ω.
  - ✓ The ZF is routed back to the δN evolution and produces a finite PV flux at the ZF onset time.
  - ✓ The aligned radial structures of the ZF-induced flux $\Gamma_{\langle\delta\phi\rangle}$ and Γ_Ω persists during the whole ZF build-up phase, and a positive feedback between $\Gamma_{\langle\delta\phi\rangle}$ and Γ_Ω effectively works.
  - ✓ As a consequence, Γ_Ω and thus ZF significantly increase.
- In the absent of $U'_{\parallel 0}$,
  - ✓ the radial structure of $\Gamma_{\langle\delta\phi\rangle}$ is inconsistent with that of Γ_Ω at the ZF onset time.
  - ✓ The phase difference between the radial structures of $\Gamma_{\langle\delta\phi\rangle}$ and Γ_Ω hinders the initiation of their positive feedback.
  - ✓ At the saturation time, however, the phases of the radial structures of $\Gamma_{\langle\delta\phi\rangle}$ and Γ_Ω are synchronized in the inner region. Thus, Γ_Ω can significantly increase.



Radial profiles of zonal flows with $U'_{\parallel 0} = 0.0$ and $U'_{\parallel 0} = 1.6$ at the zonal flow onset time t_{ZF0}(a) and turbulence saturation time t_{SAT} (b).



Contributions of the gyro-center density evolution mechanisms to the PV flux as a function of radius at the zonal flow onset time t_{ZF0}(a) and turbulence saturation time t_{SAT} (b) in the case with $U'_{\parallel 0} = 1.6$ and $R_0/L_{T0} = 5.2$.



Results of the PV transport analysis in the case with $U'_{\parallel 0} = 0.0$ and $R_0/L_{T0} = 5.2$. in the same format with the above figure.