Transport hysteresis and zonal flow stimulation in magnetized plasmas

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Understanding transport in tokamak plasma is an important step toward viable nuclear fusion [1]. A study of zonal flows generated by trapped-electron mode (TEM) and trapped-ion mode (TIM) micro turbulence is presented. For this purpose the gyrokinetic code TERESA (Trapped Element REduction in Semi lagrangian Approach), which considers only trapped particles, is used [2, 3, 4, 5, 6, 7, 8]. The model enables the processing of the full f problem for trapped ions and electrons at very low numerical cost. In this paper we show that in some parameter range in gyrokinetic simulations, it is possible to apply a control method to stimulate the appearance of zonal flows while minimizing the duration of the control process and the impact on plasma parameters [9]. We also report on our observation of a hysteresis in the relation between zonal flows and electron temperature [10].

Trapped particles

The motion of a single trapped particle in a tokamak can be divided into three parts: The fast cyclotron motion (ω_c, ρ_c), the bounce (or "banana") motion (ω_b, δ_b), and the precession drift along the toroidal direction (ω_d, R), with $\omega_d \ll \omega_b \ll \omega_c$ and $\rho_c \ll \delta_b \ll R$ (See Fig.1).

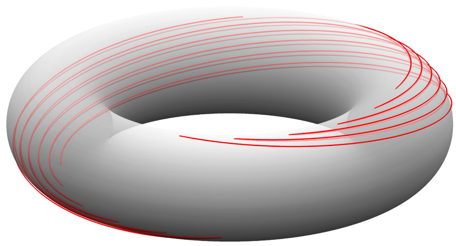

Figure 1: *Trapped particles in a tokamak.*

The turbulence driven by trapped particles is characterized by frequencies of the order of the precession frequency ω_d. Averaging over both cyclotron and bounce motions filters the fast frequencies ω_c and ω_b and the small space scales ρ_c and δ_b. It reduces the dimensionality of the kinetic model from 6D to 4D:

$$\bar{f}_s = \bar{f}_{\mu,E}(\psi,\alpha)$$

with $\bar{f}_s$ the "banana center" distribution function, $\alpha = \varphi - q\theta$ and ψ the poloidal flux ($d\psi \sim -dr$). φ and θ are the toroidal and poloidal coordinates, and q is the safety factor. Only two kinetic variables appear in the differential operators. The two other variables appear as parameters - two adiabatic invariants, namely particle kinetic energy E and μ the 1st adiabatic invariant.

Model

The Vlasov equation per species (with two species, $s = i, e$) writes:

$$\frac{\partial \bar{f}_s}{\partial t} - \frac{\partial J_{0s}\Phi}{\partial \alpha}\frac{\partial \bar{f}_s}{\partial \psi} + \frac{\partial J_{0s}\Phi}{\partial \psi}\frac{\partial \bar{f}_s}{\partial \alpha} + \frac{\Omega_d E}{Z_s}\frac{\partial \bar{f}_s}{\partial \alpha} = 0$$

The normalized quasi-neutrality constraint writes:

$$\frac{2}{\sqrt{\pi} n_{eq}}\left(\underbrace{\int_0^{+\infty} J_{0i}\bar{f}_i E^{1/2} dE}_{Trapped\ ions} - \underbrace{\int_0^{+\infty} J_{0e}\bar{f}_e E^{1/2} dE}_{Trapped\ electrons}\right) = \frac{1}{T_{eq,i}}\left[\underbrace{C_{ad}(\Phi - \varepsilon_\phi \langle\Phi\rangle)}_{Passing\ particles} - \underbrace{C_{pol}\bar{\Delta}_{i+e}(\Phi)}_{Polarisation}\right]$$

with $J_{0s} = \left(1 - \frac{E}{T_{eq,s}}\frac{\delta_{b0,s}^2}{4}\partial_\psi^2\right)^{-1}\left(1 - \frac{E}{T_{eq,s}}\frac{q^2\rho_{c0,s}^2}{4a^2}\partial_\alpha^2\right)^{-1}$ the gyro-bounce-average operator.

The gyrokinetic code currently runs this 4D model for N kinetic trapped species. A semi-Lagrangian scheme is used in order to solve the Vlasov equations. To solve the quasi-neutrality, the fields are first projected in the Fourier space along the periodic direction α and then the electric potential Φ is a solution of a second order differential equation in ψ.

Zonal flows versus streamers - Stimulate zonal flows

Starting from a situation where $T_e = 2T_i$, we observed that zonal flows occur at the beginning of the nonlinear phase and then are reduced allowing for streamers to govern heat radial transport. As a control method to stimulate zonal flows it is proposed to temporarily drop T_e (see Fig. 2) as we observed zonal flows to be strong and robust in the $T_e/T_i = 1$ case. This can be interpreted as a crude model for a temporary drop in ECRH. Starting from a situation where $T_e = 2T_i$, we decide to stop the electron heating ($T_e = T_i$) for a short period of time and then to heat the electrons again ($T_e = 2T_i$) with the aim of obtaining strong and robust zonal flows.

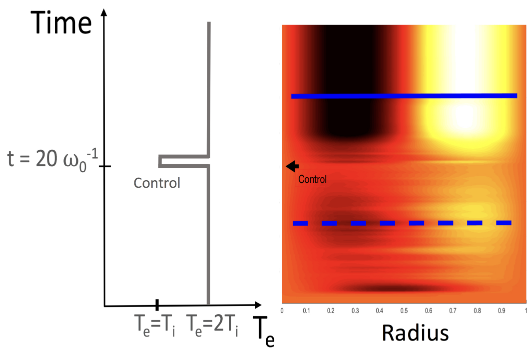

Figure 2: *Electron heating is switched off during a short time (0.25 ω_0^{-1}, at $t = 20\ \omega_0^{-1}$). Zonal potential Φ_{ZF} is plotted against radius and time.*

The results are given Fig. 2 and 3. The amplitude of these zonal flows is almost constant after $t = 25\ \omega_0^{-1}$, and until we arbitrarily end the simulation (we have checked up to $t = 250\ \omega_0^{-1}$). Therefore, robust and strong zonal flows appear to be triggered by the applied control. It should be noted that we found the qualitative response of the plasma to be insensitive to the duration of the control period during which we modify the plasma parameters.

This behavior can also be seen in Fig. 4 where the electric potential shearing rate profile is plotted against ψ for both cases for two different times (at $t = 11.5\ \omega_0^{-1}$, before control, dotted line and at $t = 30.0\ \omega_0^{-1}$, after control, solid line). As we can note, the zonal flows at $t = 30.0\ \omega_0^{-1}$ recovered with the control method are much stronger than those observed at the same time without any control. Clearly the control method is very effective throughout most of the domain, and therefore a high level of improvement in energy confinement can be expected globally.

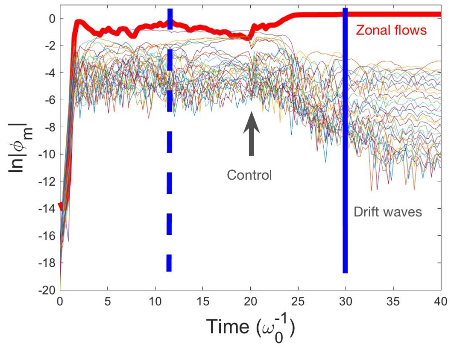

Figure 3: *Amplitude of the electric potential plotted against time. The mode $m = 0$ (in red) is the zonal flow potential. Other modes correspond to drift modes.*

Hysteresis in the relationship between zonal flows and electron heating

A hysteresis in the relationship between zonal flows and electron heating is observed numerically by using gyrokinetic simulations in fusion plasmas [10]. To quantify the strength of zonal flows and drift instabilities, we define the energy contained in the zonal flow:

$$W_{ZF} = \int_0^1 \left\langle \frac{\partial \phi}{\partial \psi} \right\rangle_\alpha^2 d\psi$$

and the energy contained in drift instability modes:

$$W_{m>0} = \int_0^1 \left\langle \left(\frac{\partial \phi}{\partial \psi} - \left\langle \frac{\partial \phi}{\partial \psi} \right\rangle_\alpha \right)^2 \right\rangle_\alpha d\psi$$

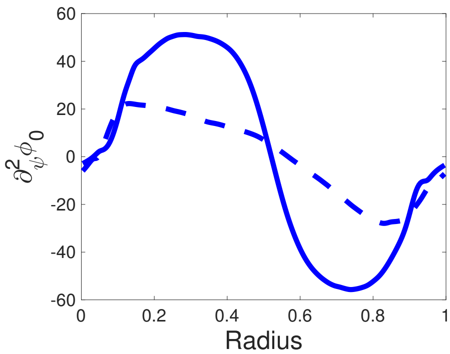

Figure 4: *Zonal electric potential shearing rate as a function of radius, without control (dotted line, $t = 11.5\ \omega_0^{-1}$) and with control (solid line, $t = 30\ \omega_0^{-1}$).*

Here $< . >_\alpha$ means average over α, and m is the mode number along the α direction.

As the electron temperature increases, a first transition occurs (from A to B, see Fig. 5), at a given electron/ion temperature ratio, above which zonal flows are much weaker than before the transition, leading to a poorly confined plasma. Beyond this transition, even if the electron temperature is lowered to a moderate value, the plasma fails to recover a dynamic state with strong zonal flows. Then, as the electron temperature decreases further, a new transition appears (from C to D), at a temperature lower than the first transition, below which the zonal flows are stronger than they were initially.

The confinement of the plasma and the heat flux are thus found to be sensitive to the history of the magnetized plasma. These transitions are associated with large exchanges of energy between the modes corresponding to instabilities ($m > 0$) and zonal flows ($m = 0$). We also observe that up to the first transition it is possible to use the control method described above to stimulate the appearance of zonal flows and therefore the confinement of the plasma. Beyond that transition, this control method is no longer effective.

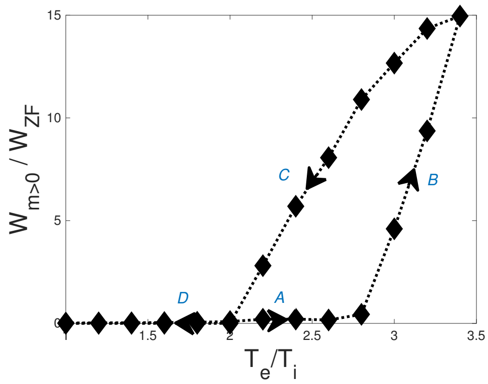

Figure 5: $W_{ZF}/W_{m>0}$ *plotted against* T_e/T_i*. The arrows indicate the path of the hysteresis, according to electron heating.*

Conclusion

We used a gyro-bounce-kinetic code. We investigated the possibility of stimulating zonal flow generation. Zonal flows are driven by TEM and TIM turbulence and studied by means of gyrokinetic Vlasov simulations for trapped particles. We have shown that in cases where zonal flows normally appear only transiently at the beginning of a simulation it is possible to trigger a bifurcation from a standard steady-state dominated by radially-elongated structures, to a new steady-state dominated by zonal flows, by shortly increasing the T_i/T_e ratio. We also studied the exchange of energy between zonal flows and instabilities as a function of the electron temperature. The change was found to have the characteristics of hysteresis and the plasma may have different dynamic states according to the history of the electron temperature. Two major transitions were observed during this hysteresis cycle: One for which instabilities suddenly develop, and the other for which the zonal flows strongly take over instabilities.

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