Global gyrokinetic simulations of trapped-electron mode and trapped-ion mode microturbulence

E. Gravier, T. Reveille, T. Drouot, M. Lesur

Institut Jean Lamour - UMR 7198 - University of Lorraine, Nancy, France

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]. The model enables the processing of the full f problem for trapped ions and electrons at very low numerical cost. TEM or TIM linear growth rates obtained with the full f nonlinear code have been successfully compared with analytical predictions [3, 4]. The influence of the banana width on the number of zonal flows occurring in the system has been studied using the gyrokinetic code and the impact of the temperature ratio T_e/T_i on the reduction of zonal flows have been shown [5]. In this paper we focus on a related control method to stimulate the appearance of zonal flows while minimizing the duration of the control process [6].

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).

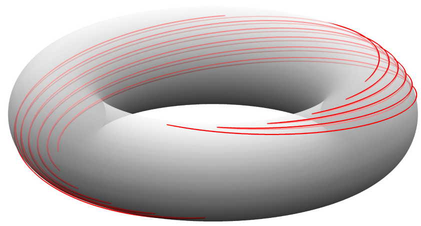

Figure 1: *Trapped particles in a tokamak.*

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 ($\psi \sim -r$). φ and θ are the toroidal 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 the first adiabatic invariant μ.

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.

Electrostatic potential

Figure 2 shows the behavior of the electric potential fluctuations as a function of α and ψ at different times. Instabilities and streamer structures are found to develop according to the most unstable mode n. Small structures appear as a consequence of the most linear unstable mode growing ($t = 3\ \omega_0^{-1}$). Then, due to the nonlinear mode coupling, these structures coalesce leading to a saturated state dominated by large scale structures ($t = 13$ and $t = 39$ ω_0^{-1}). Some small structures reappear after this saturation phase ($t = 45\ \omega_0^{-1}$) and later disappear again.

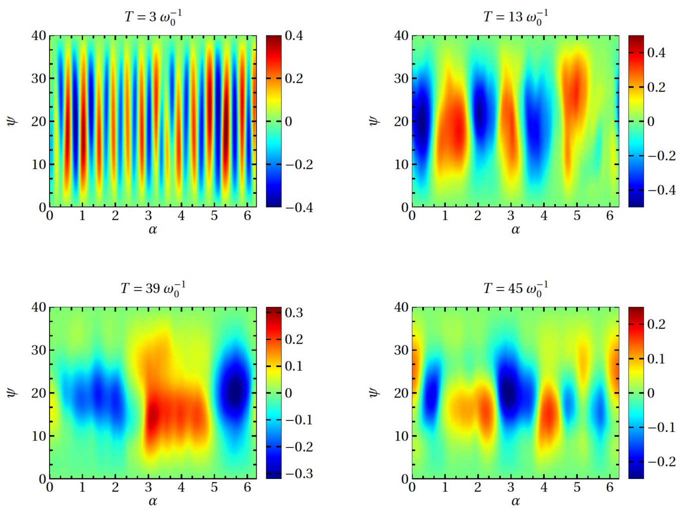

Figure 2: *Electrostatic potential Φ as a function of α and ψ, at different times. Streamers are observed in this case.*

As expected for a two-dimensional flow, small structures coalesce as a consequence of the nonlinear mode coupling leading to a saturated state dominated by large scale structures. This inverse cascade process leads to the formation of large scale structures by transferring the energy of one mode towards smaller mode numbers. Enstrophy cascades to smaller scales are also possible, in opposite directions away from the source region [3].

Zonal flows versus streamers - Stimulate zonal flows

As a control method to stimulate zonal flows it is proposed to temporarily drop T_e (see Fig.3). This can be interpreted as a crude model for a temporary drop in ECRH. ECRH is a powerful heating tool with which heating energy may be deposited at selected locations, thus tailoring the temperature profile in the plasma. ECRH is used in many tokamaks - the ITER Tokamak will rely on ECRH heating - and is also for instance the main heating system of Wendelstein 7-X, capable to operate continuously. 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.

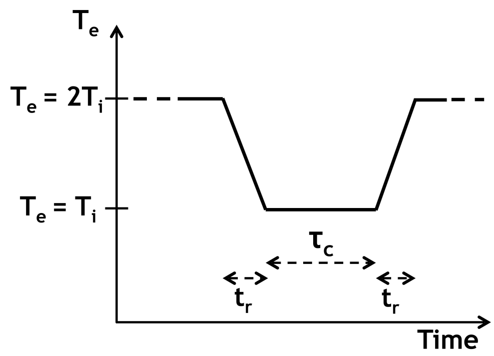

Figure 3: *Principle of the control method.*

Since we have observed zonal flows to be strong and robust in the $T_e/T_i = 1$ case, we try to apply this temperature ratio to the system between $t = 20$ and $t = 20.26\ \omega_0^{-1}$. After this time the temperature ratio is brought back up to its initial value $T_e/T_i = 2$. The results are given in Fig.4. Note that $\psi \sim -r$. 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. 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.

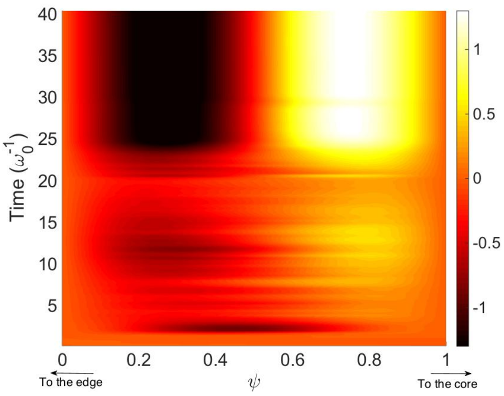

Figure 4: *Zonal potential Φ_{ZF} as a function of ψ and time for $T_e = 2T_i$. The control method was applied between $t = 20$ and $t = 20.26$.*

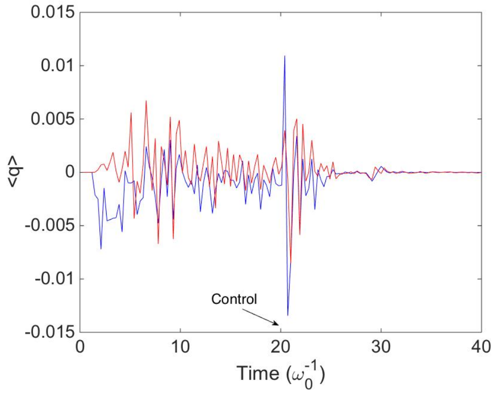

Figure 5: *Conductive electron q_e (in red) and ion q_i (in blue) heat fluxes as a function of time.*

Heat transport from the hot plasma core towards the colder plasma boundary is highly connected to the turbulence level and the competition between zonal flows and streamers. Our aim is to reduce heat fluxes by stimulating zonal flows. Figure 5 shows the conductive heat flux q_s averaged over α and ψ, as a function of time. The effect of the control on the heat flux is clearly noticeable. After the control was applied at $t = 20\ \omega_0^{-1}$ and after a transition period of about 5 ω_0^{-1}, the system stabilizes and reaches a steady state in which the heat flux is reduced.

To quantify this effect, the ion heat flux is averaged over time from $t = 25$ to $t = 40\ \omega_0^{-1}$. In the case without control, $< q_i >_t$ is found to be approximately -10^{-3}, whereas in the case with control $< q_i >_t$ is strongly reduced as expected and is equal to -6.5×10^{-5} thus proving the efficiency of the control method in reducing the radial heat transport. Here the heat transport is carried mainly by the trapped ions and transported outwards (downgradient).

Conclusion

We used a gyro-bounce-kinetic code. 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 streamers, to a new steady-state dominated by zonal flows, by shortly decreasing the T_e/T_i ratio. Although this is not described in this paper, several numerical models for the control method were tested. It is possible to modify the plasma behavior by changing the C_{ad} coefficient which is a function of the electron temperature or by modifying the boundary conditions *i.e.* the temperatures of the thermal bath or both. We also observed that the plasma dynamics is not affected by the duration of the control applied.

References

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