Effect of self-generated zonal flows on turbulent heat transport in a tokamak plasma

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Abstract. A major goal in fusion research is understanding the anomalous thermal transport of energy and particles in a tokamak. In particular, a crucial issue is the origin of its empirical dependence on the various dimensionless parameters controlling the energy confinement. This paper addresses the impact of ion-ion collisions and of self-generated zonal flows (large-scale ExB sheared poloidal flows) on turbulent ion thermal transport, in the core of a tokamak plasma. A three-dimensional fluid model is used, which describes flux-driven electrostatic plasma turbulence, generated by Ion Temperature Gradient (ITG) instabilities. The model includes curvature effects, parallel Landau damping and a collisional damping of the poloidal flows. Simulation results show a stabilization of the turbulence and a rise of the energy confinement time when the collisionality is lowered, that is when the zonal flows are weakly damped by ion-ion collisions. The mechanism responsible for the turbulence stabilization at low collisionality is identified as the non-linear upshift of the effective threshold for the ITG turbulence onset. This upshift is governed by an increase of the zonal flow shear.

1. Introduction

Understanding thermal transport in a tokamak plasma is a major goal in fusion research. Indeed predictions of the performance of future fusion reactors are based on extrapolations of the empirical scaling laws of energy confinement and transport, beyond the experimental parameter range. A crucial question is the origin of the empirical dependence of the heat turbulent transport on the dimensionless parameters that control the energy confinement in a tokamak [1]. It has been theoretically demonstrated [2, 3] that the scaling of plasma energy confinement can be expressed in terms of few dimensionless quantities and other geometrical or physical parameters of a tokamak. The scaling of turbulent transport in terms of the normalised Larmor radius \( \rho_s = \rho_s/a \) (where \( \rho_s \) is the ion-sound Larmor radius and \( a \) the minor radius of a tokamak), has been addressed by several works, however, the results are somewhat controversial: fluid simulations indicate that the thermal conductivity scales as \( \chi \sim \rho_s \chi_{Bohm} \), so-called gyro-Bohm scaling (with \( \chi_{Bohm} = (cT_e)/(eB) \) the Bohm conductivity) [4, 5] [6], whereas kinetic simulations show a Bohm-like scaling [7]. The dependence on the dimensionless parameter \( \beta \) (ratio of the plasma kinetic pressure to the magnetic field pressure) and on the collisionality \( \nu_s = \nu_{ii}/\omega_{detrapp} \) (ion-ion collisionality normalised on the particle detrapping frequency), is still an unresolved issue. In this work we address the impact of the collisionality on the electrostatic turbulent transport in the core of a tokamak plasma.
Thermal losses in a tokamak plasma are determined in first place by collisional processes, although, those cannot account for the large transport measured in the plasma core. This thermal transport is defined as anomalous, since the measured diffusivity is larger than the neoclassical one by one or two orders of magnitude. Its origin is attributed to turbulent mechanisms, which are still not completely understood.

Theoretical and experimental evidence has been given that the underlying turbulent fluctuations originate from microinstabilities, unstable waves or modes characterized by wavelengths much smaller than the macroscopic scale-lengths of the machine. One of the main sources for instabilities in a magnetised plasma are equilibrium inhomogeneities, such as density or temperature gradients, which induce the generation of drift-waves. A feature of those plasma modes is the presence of a threshold, usually a critical gradient length, above which the drift-waves become unstable and are finally able to produce a turbulent convection in the plasma. In particular, for the Ion Temperature Gradient (ITG) driven modes, which are the instabilities considered in this work, a critical gradient of ion temperature exists.

A tokamak plasma is a strongly anisotropic system since the plasma is confined by means of a strong magnetic field along the large circumference of the torus (toroidal direction) and a much weaker field along the small circumference (poloidal direction); this produces a strongly bidimensional dynamics. Like in many bidimensional fluids an "inverse cascade" generally takes place, characterized by the generation of large scales. However, contrarily to fluids, a plasma is characterised by the presence of wave-particle interactions such as the Landau resonances, that damp the perturbations with a short wavelength in the direction parallel to the magnetic field. A consequence is that, in the presence of a sheared magnetic field, large perpendicular scales are also damped, which limits the cascade process. The largest scale of the system is finally proportional to the Larmor radius, hence the generation of microturbulence. Landau damping also limits the correlation lengths and times, as well as the fluctuation amplitudes, as it will emerge more clearly later in this work.

A turbulent plasma can also be considered as a complex system in which self-organization occurs, leading to the self-generation of large coherent structures. In particular, large-scale $E \times B$ flows, the so-called zonal flows, are self-generated by the poloidal component of the turbulent Reynolds’s stresses [8] and can then back-react regulating the turbulence. Those flows are of great importance since they are easily excited in the system and are not damped by the Landau resonant mechanism depicted above. Zonal flows are symmetric in the periodic directions of the torus and very localised radially, their direction and magnitude varying along the radius (sheared flows). The generation of such poloidal flows in the system introduces a further anisotropy between the poloidal and radial direction. The main element in the dynamics of the large-scale zonal flows is the process of shearing of the turbulent eddies, the radially extended convection cells are stretched and broken. It has been ascertained that such a process has a stabilizing effect on turbulence, leading to a reduction of the radial transport [9]. The interaction of drift-wave turbulence with the zonal flows can be modelled in terms of a predator-prey system [10].

Ion-ion collisions play a subtle role in the mechanism of regulation of drift-wave turbulence by its self-generated zonal flows. Although the underlying microturbulence is essentially collisionless, evidence was highlighted that in collisionless plasmas an undamped component of the poloidal flows persists, which is ultimately damped by ion-ion collisions [11]. This observation suggests a way by which the ion-collisionality can affect the overall transport: it provides a balance to the Reynolds stresses which drive zonal flows, by means of damping those flows. If the damping by ion-ion collisions is low, the zonal flows are able to develop and thus back-react on the turbulence, regulating the transport.
Previous studies addressed this question with both fluid and kinetic models [12, 13],[14, 15] showing the stabilizing effect of zonal flows on the thermal transport, when the collisionality is low. In this work we address the question of understanding the mechanism underlying the turbulence stabilization by collisionally damped zonal flows, solving numerically a simplified fluid model, which aims to reproduce a reactor-like situation (steady state conditions) and takes into account the main physical ingredients of the complex turbulent system.

We would like to stress that in a complex system including micro-instabilities and large-scale zonal flows very different spatial scales coexist; this will be highlighted in the rest of the paper. Also, at least two different time-scale are present: a turbulent time scale and a global transport time-scale, which is almost two orders of magnitude larger then the turbulent one. Therefore, the model to be used for the purpose of this study is necessarily a global model, in which no a priori assumptions are made on the size of turbulent structures nor on scale separation. Concerning the time scales, the simulations are carried on until the system is stationary on the longest time scale, typically for a duration of a few energy confinement times (the energy confinement time being defined as the ratio of the injected power to the power losses of the system).

2. The physical model
In order to describe the complex system composed of electrostatic ITG turbulence and zonal flows in a tokamak plasma, a minimal three-dimensional fluid model is required [16], consisting of the evolution equations of three macroscopic scalar fields, which are advected by the $E \times B$ velocity: the ion density, the velocity parallel to the magnetic field and the ion pressure. Electrons are assumed to be adiabatic and the quasi-neutrality relation is used to provide a closure to the system.

The equations are solved on a toroidal annulus, having circular section. The system is forced by means of the injection of a fixed heat flux $F_{in}(r_a) = \chi(r_a)\nabla p_i(r_a)$, at the inner boundary $r_a$. The model equations are derived to the leading order of the expansion in the small parameter $\varepsilon = a/R$, which represents the tokamak inverse aspect ratio (ratio of the tokamak minor radius to the major radius).

The normalised model equations are the following [16]:

\begin{align}
\left( \frac{\partial}{\partial t} + \vec{v}_E \cdot \nabla \right) w - 2 \varepsilon \omega_d (\Phi + p_i) + A \nabla_{\parallel} v &= - A \gamma_{pfd} < w > + D_w \nabla^2 w; \\
\left( \frac{\partial}{\partial t} + \vec{v}_E \cdot \nabla \right) v + A \nabla_{\parallel} (\Phi + p_i) - 4 \varepsilon \omega_d v &= D_v \nabla^2 v, \\
\left( \frac{\partial}{\partial t} + \vec{v}_E \cdot \nabla \right) p_i + \Gamma A \nabla_{\parallel} v - 2 \Gamma \varepsilon \omega_d (2 p_i + < \Phi >) &= - \gamma_L |\nabla_{\parallel}| p_i + D_p \nabla^2 p_i;
\end{align}

where

\[ w = \Phi - < \Phi > - \rho_s^2 \nabla^2 \Phi \]

is the ion guiding center density and $\Phi$ the electrostatic potential.

The main control parameters of the model are the normalised ion sound Larmor radius $\rho_s = \rho_s/a$ , the inverse aspect ratio $\varepsilon = a/R$, the injected heat flux, which enters in the equations through the viscous diffusivity, and the damping rate of poloidal flows $\gamma_{pfd}$.

The equations are solved on a toroidal annulus, between two magnetic surfaces. The circular magnetic surfaces are identified by the coordinates $r$, $\theta$ and $\varphi$, respectively radial coordinate, poloidal and toroidal angle.
The model describes a turbulent system with a threshold, i.e., on the ion temperature gradient for the chosen case of ITG instabilities. The main drive for the instability is provided by the curvature terms, \( \omega_d = \sin \theta \partial_t + \frac{1}{2} \cos \theta \partial_\theta \) being the curvature operator; besides this operator is responsible for a coupling between neighboring poloidal modes.

The other quantities introduced in the equations above are defined as follows. The advection operator is defined as \((\partial_t + \vec{v} \cdot \nabla)\), where \(\vec{v} = -\left(\nabla \Phi \times B\right)/B^2\) is the \(E \times B\) velocity. \(\nabla_\parallel = \partial_\theta + \frac{1}{q} \partial_\phi\) is the parallel derivative operator, with \(q\) the safety factor; \(<.>\) represents an average over a magnetic surface (i.e., over the angles). \(A = \varepsilon/\rho_s\) and \(\Gamma = 5/3\).

Lengths are normalised to the minor radius \(a\), the parallel velocity to the ion sound velocity \(c_s = \sqrt{T_e/m_i}\), the ion pressure to \(n_0 T_e\) and potential to \(T_e/e\); time and conductivity are in Bohm units \(t_{Bohm} = a^2/\chi_{Bohm}, \chi_{Bohm} = (eT_e/eB)\).

A simple closure, modelling the parallel Landau damping, is introduced by the absolute value of the parallel gradient operator applied to the ion pressure in Equation (3); the parameter \(\gamma_L\) is chosen of order unity. Small artificial perpendicular dissipation coefficients, \(D_{w,v,p}\), have been introduced to damp the small scales \((D \sim 10^{-3} \text{ for an injected flux of order unity})\).

Finally, the damping of poloidal flows is modelled through a damping rate \(\gamma_{pfd}\) applied to the average component of the guiding center density, i.e., to the polarization current, in Equation (1). Using the damping rate derived in [11] \(\gamma_{pfd} = 2/3 \nu_s \varepsilon^{1/2}/q\), thus the model parameter is proportional to the collisionality \(\nu_s = \nu_{ii} \varepsilon^{-3/2}/(c_s/qR)\), where \(\nu_{ii}\) is the ion-ion collision frequency.

For the numerical implementation finite differences are used in the radial direction whereas the angles are represented by their Fourier components, \(m\) and \(n\) respectively poloidal and toroidal wavenumbers.

3. Effect of collisionally damped zonal flows on electrostatic ITG turbulence

The main purpose of this work is to assess the impact of ion collisions on turbulent thermal transport. Numerical simulations have been performed with the ETAI3D code [4], imposing a fixed injected heat flux and reducing the ion-ion collisionality by steps, in order to approach values relevant to the operative regime of a future fusion reactor, \(\nu_s \ll 1\). Precisely, simulations are carried on until a turbulent stationary state is reached, typically for a couple of energy confinement times, then the collisional damping of zonal flows is abruptly reduced and the simulation is continued till a new stationary state is obtained. The effect of collisions and of the self-generated zonal flows on the turbulent thermal transport is thus analyzed in a turbulent steady state, for different fixed injected fluxes, reproducing a machine-like situation.

3.1. Simulation parameters

A series of simulations has been performed for the case of a torus having normalized Larmor radius \(\rho_s = 0.02\), injected fluxes \(F_{in} = 0.05, 0.2\) (measured in units of \(\rho_s c_s T_e n_e\)) and values of the collisional poloidal flow damping \(\gamma_{pfd} = 0.5 \pm 0.1\), corresponding to values of the collisionality \(\nu_s = 3.5 \div 0.7\), evaluated at mid-radius. The same simulations have been repeated halving both \(\rho_s\) and \(F_{in}\).

A flat density profile and a monotonic safety factor profile \(q = 4r\) (corresponding to unity magnetic shear) are chosen and an inverse aspect ratio \(\varepsilon = 0.25\). A typical resolution of \(82 \times 128 \times 64\) (number of radial mesh points x poloidal x toroidal modes) and a timestep \(\Delta t = 5 \cdot 10^{-4}\) are used for the case with \(\rho_s = 0.02\); a finer radial and temporal resolution is needed for cases with steep profiles.

3.2. Simulation results

Figure 1 shows the temporal evolution of the r.m.s (root mean squared) fluctuation amplitudes of the three fields pressure (blue), electrostatic potential (red) and parallel velocity (green), for
a case of a torus having $\rho_s = 0.02$, with $F_{in} = 0.05$ and $\gamma_{pfd} = 0.25$. The collisionality is halved at time $t = 40$. It can be observed that the reduction of collisional damping is followed by a drastic drop of the fluctuation amplitudes. Subsequently, the fluctuations rise again, as well as the pressure gradient, until a new turbulent steady state is reached when the turbulent losses balance the injected heat flux (which we remind is injected into the system at a constant rate during the all simulation). It was verified [16] that this turbulence stabilization is an effect of the increased zonal flow shearing rate, which overcomes the most unstable ITG mode linear growth rate, transiently stabilizing the fluctuations.

**Figure 1.** Temporal evolution of the r.m.s fluctuation amplitudes of pressure (blue full line), electrostatic potential (magenta full line) and parallel velocity (dashed line), for a case of a torus having $\rho_s = 0.02$, with $F_{in} = 0.05$. $\gamma_{pfd} = 0.5$ until $t = 40$, $\gamma_{pfd} = 0.25$ afterwards. A sudden drop in the fluctuation amplitudes follows the damping reduction. (Time is in Bohm units).

**Figure 2.** Spectrum of the fluctuating electrostatic potential for a case with $\rho_s = 0.02$ and $F_{in} = 0.05$, at mid-radius. Contours are plotted on the plane $(n, m)$ (toroidal versus poloidal wavenumber) at $t = 39$ in the turbulent steady state with $\nu_s = 1.75$ (a) and at $t = 41$ just after $\nu_s$ is set to 0.7 (b). The spectrum shows two peaks at $(n, m) = (0, 1)$ and $(n, m) = (-6, 18)$ in case (a) of maximum fluctuation amplitude $\sim 1 \cdot 10^{-2}$, whereas in case (b) a max. amplitude of $\sim 8 \cdot 10^{-3}$ is shown on mode $(n, m) = (-5, 16)$. 
In reference [16] we had shown that the low collisionality state corresponds to an increase of the energy confinement time. It was also shown there that the radial velocity r.m.s amplitude also drops when the collisionality is reduced; this affects the radial turbulent flux, defined as $\Gamma_r = \langle \delta p \delta v_r \rangle$, corresponding to a reduction of the net radial turbulent transport. This transport reduction is not only due to a drop of the fluctuation amplitudes (the cross-phase between pressure and radial velocity fluctuations being unvaried in the analyzed case), but also to a change in the spectrum of fluctuations. We present here an example of the variation of the spectrum of fluctuations for a case with $\rho_\ast = 0.02$ and $F_{in} = 0.05$. In Figure 2, contours of the fluctuating electrostatic potential are plotted on the plane $(n, m)$ (toroidal versus poloidal wavenumber) at two different instants: at $t = 39$ in the stationary state with $\nu_\ast = 1.75$ (a) and at $t = 41$ just after the collisionality has been reduced to $\nu_\ast = 0.7$ (b). It is evident that after the sudden decrease of the collisionality, the amplitude of fluctuations diminishes over the entire spectrum.

**Figure 3.** Contours of the radial turbulent heat flux versus time, for a case of a torus with $\rho_\ast = 0.02$, $F_{in} = 0.05$ and $\nu_\ast = 3.5$. At time $t = 20$ the collisional damping is set to zero.

**Figure 4.** Contours of the radial turbulent heat flux versus time, in the turbulent steady state with $\nu_\ast = 0.7$ (a) and $\nu_\ast = 3.5$ (b), for a case with $\rho_\ast = 0.02$ and $F_{in} = 0.05$.

The temporal evolution of the radial turbulent heat flux $\Gamma_r$ is shown in Figure 3, also for a case of a torus having $\rho_\ast = 0.02$ and $F_{in} = 0.05$. The simulation was initialised with a strong damping of the zonal flows $\gamma_{pf/d} = 0.5$ ($\nu_\ast = 3.5$) and let evolve for a duration of a couple of energy confinement times. The contour plot of the radial turbulent flux in the $(r, t)$ plane...
exhibits large scale radial correlations, in the sense that the flux increases or decreases almost synchronously across a large region. This phenomenon can be related to the occurrence of avalanches (rapid transport events over a large spatial extension). At time $t = 20$ the collisional damping of zonal flows is now set to zero (undamped zonal flows); one can observe that, in parallel to a strong reduction of the turbulent flux, radial correlations are also strongly reduced. In Figure 4 the radial turbulent heat flux evolution over 4 time units is shown, in the turbulent steady state corresponding to the previous case with $\nu_s = 3.5$ (b) and in a stationary state obtained reducing in two steps the collisionality up to the value $\nu_s = 0.7$ (a). In the latter state at low collisionality, the flux amplitude is reduced; at the same time, smaller scale radial correlations of the flux can be observed.

The mechanism responsible for the net turbulence stabilization at low collisionality is the zonal flow damping: a reduction of ion-ion collisions increases the zonal flow shear, thereby rising the effective temperature threshold for the ITG instabilities. As a consequence, the effective ion heat conductivity increases with collisionality. Figure 5 shows the profiles of the ion heat conductivity averaged on the steady states corresponding to different values of collisionality, for the previous simulations.

The dependence of the turbulent thermal transport on the normalised Larmor radius had been previously analyzed in ref.[4],[5], where a gyro-Bohm scaling $\chi \sim \rho^* \chi_{\text{Bohm}}$ was highlighted, as mentioned in the introduction. Note that the gyro-Bohm dependence of transport on $\rho^*$ has been confirmed for the case of different collisionalities, by means of comparing the simulation cases analyzed here with self-similar simulations, i.e. halving both $\rho^*$ and $F_{\text{in}}$, so that the same heat conductivity is expected for a gyro-Bohm scaling.

![Figure 5. Comparison of the ion heat diffusivity profiles, averaged over the steady state with $\nu_s = 3.5$ (full line), $\nu_s = 1.75$ (dashed line) and $\nu_s = 0.7$ (dash-dotted line), for a case with $\rho_s = 0.02$, $F_{\text{in}} = 0.05$. Bohm units are used.](image)

### 3.3. Statistical analysis

Time autocorrelation functions have been evaluated for the fluctuating and zonal component of the electrostatic potential in stationary state, averaging over the poloidal and radial coordinates and over several turnover times, typically over two confinement times. A typical case is plotted in Fig. 6, corresponding to a simulation with $\rho_s = 0.02$ and $F_{\text{in}} = 0.05$. The time autocorrelation functions for the fluctuating component plotted in full line, decay exponentially, as expected for most chaotic systems; whereas the autocorrelation of the zonal component (dashed lines) is much larger. It is evident, that the turbulence correlation time, $\tau_{\text{corr}} \sim 10^{-2} t_{\text{Bohm}}$, is an order of magnitude smaller than that of the zonal flows. This clearly shows that the zonal flows evolve much more slowly than the ambient turbulence, suggesting that zonal flows are frozen. This can be of practical use for analytic calculations, since it allows to separate the time-scales of
turbulence and of zonal flows. One also observes that the turbulence correlation times strongly depend on the collisionality value, decreasing with collisionality: \( \tau_{\text{corr}} \sim 7 \cdot 10^{-1} t_{\text{Bohm}} \) for \( \nu_s = 3.5 \) and \( \tau_{\text{corr}} \sim 2.6 \cdot 10^{-2} t_{\text{Bohm}} \) for \( \nu_s = 0.7 \). On the contrary the zonal flow correlation time exhibits an inverse dependence.

Two-point radial correlation functions for the fluctuating electrostatic potential and its zonal component have also been evaluated for the same simulation, in the stationary state, averaging over the poloidal coordinate and over a confinement time. It is interesting to note that whereas the correlation functions for the fluctuating component decay exponentially and do not present significant tails at large radial separation, the zonal flow component shows an oscillation of several Larmor radii of amplitude. The radial correlation functions have been observed to be self-similar for different tokamak sizes, scaling with \( \rho_s \) [17]. Also, the turbulence correlation lengths slightly decrease at low collisionality, whereas the zonal flows correlation length shows the inverse dependence. The typical radial size of turbulent structures is of the order of few Larmor radii, varying for the above case from \( \lambda_{\text{corr}} \sim 3.2 \rho_s \) for \( \nu_s = 3.5 \) and \( \lambda_{\text{corr}} \sim 2.2 \rho_s \) for \( \nu_s = 0.7 \). The main effect of the stronger zonal flow shear at low collisionality is therefore a reduction of both the turbulence correlation time and lengths.

### 3.4. Uniqueness of the turbulent stationary state

The theoretical question of the existence of a unique attractor for the chaotic system under study, can be motivated by the experimental observation of an hysteresis in a tokamak plasma, when a transition occurs from a low confinement regime to an improved confinement one, and back. The uniqueness of the turbulent stationary state of the system has been tested by means of restarting a simulation from the final turbulent steady state with collisionality \( \nu_s = 0.7 \) and reverting the simulation setting again the collisionality to the value \( \nu_s = 3.5 \). This test has been carried out for the case of a torus having \( \rho_s = 0.02 \) and \( F_{\text{in}} = 0.05 \); results are shown in the graphics below. First of all, a comparison of the r.m.s fluctuation amplitudes in the two turbulent steady states, is shown in Figure 7. One can observe that the level of turbulence is almost the same for the three fields. The mean values of the fluctuation amplitudes averaged over a confinement time (\( \sim 7 t_{\text{Bohm}} \) for this case) differ of 0.5 \( \pm \) 2\%.
Figure 7. Comparison of r.m.s. fluctuation amplitudes of pressure (blue), electrostatic potential (magenta) and parallel velocity (black), averaged over the steady state with $\nu_*=3.5$ of the original simulation with $\rho_*=0.02$, $F_{in}=0.05$ (full lines) and those from the turbulent steady state obtained by running the simulation backwards (dashed lines).

In Figure 8 the pressure, electrostatic potential and velocity profiles, averaged over a confinement time in the steady state with $\nu_*=3.5$ are shown for both the simulations: the original turbulent steady state profiles are plotted in full line and the profiles of the stationary state obtained running the simulation backwards in dashed line. In Figure 9 the radial turbulent flux and the heat conductivity coefficient profiles are plotted, also averaged over the steady state (the same line definitions apply). One can observe a small variation on the average profiles which is of the order of the variation around their average value (represented by the error bars). Those results can be probatory of the existence of a unique attractor for the complex plasma system we are studying.

Figure 8. Comparison of electrostatic potential ($\Phi$), pressure and parallel velocity profiles averaged over the steady state with $\nu_*=3.5$, for the original simulation (full line) and the backward one (dashed line). Vertical error bars represent the variation of the profile around its average value.
4. Conclusions

In this paper we have presented a numerical study of the effect of self-generated zonal flows, damped by ion-ion collisions, on the turbulent heat transport in the core of a tokamak plasma. A three-dimensional fluid model describing flux-driven electrostatic ITG turbulence is used, which is implemented in the numerical code, ETAI3D. Results of the simulations carried on until steady state, with a fixed injected heat flux and different values of the ion collisionality, show that a reduction of the collisional damping of zonal flows produces a decrease of the turbulent fluctuations over the whole spectrum. Correspondingly the radial turbulent flux and the thermal transport are also reduced and an improved energy confinement is obtained at low collisionality. The origin of this turbulence stabilization at low collisionality is attributed to the upshift of the effective temperature gradient threshold for the ITG turbulence, induced by the increased shear of the zonal flows [16].

Some properties of the complex system represented by drift-wave plasma turbulence in the presence of zonal flows have been analyzed. A statistical analysis has been performed. It has been shown that the main effect of the stronger zonal flow shear at low collisionality is the reduction of both the turbulence correlation time and lengths [17]. The time autocorrelation functions for the turbulence and the zonal flow have been observed to present a different behavior, the turbulence correlation function decreases exponentially to zero, whereas the zonal flow autocorrelation function decreases much more slowly. The long time correlation of the zonal flows suggests a picture of frozen zonal flows, which can be exploitable for analytical models, since it ensures the applicability of a scale separation between the turbulence and the zonal flows. Finally, evidence has been given of the existence of a unique turbulent stationary state for given flux and collisionality, but different initial conditions.

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