Impurity transport and trapped particle modes

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In tokamak physics, impurity transport is an issue that needs to be understood in order to obtain a sustainable burning plasma. These impurities can be sputtered from the walls: in this case the impurity species will be tungsten in the context of ITER. On the other hand, the impurities can come from the plasma core, in which case they are α-particles produced by the reactions of fusion.

In this work, we focus on turbulence issues. More precisely, we look at the influence of the impurity profile on trapped particle driven modes, and study the transport of these impurities. This is done using the code TERESA. It's a semi-Lagrangian collisionless code [1, 2, 3, 4, 5], that only provides the turbulent contribution to transport. This code treats the passing particles adiabatically, and allows the study of Trapped Electron Modes (TEM) and Trapped Ion Modes (TIM). TERESA allows the processing of trapped ions, electrons, and impurities. This enables us to observe the action of the impurities as an active species, i.e. taken into account in the quasineutrality constraint, thus seeing how they influence the dynamics of the plasma, particularly on the instability growth rates and on the nonlinear phase.

Model - TERESA code

The TERESA code is based on an electrostatic reduced bounce averaged gyrokinetic model. The dynamics that will be considered here evolves on timescales of the order of the trapped particles precession frequency. Therefore it is possible to filter out the fast frequencies ω_C (cyclotron frequency) and ω_b (bounce frequency) and the small space scales ρ_c (gyro-radius) and δ_b (banana width). It reduces the dimensionality of the kinetic model from 6D to 4D:

$$f_s = f_{\mu,E}(\psi,\alpha)$$

with f_s the "banana center" distribution function, $\alpha = \varphi - q\theta$ and ψ the poloidal flux ($d\psi \sim -rdr$). φ and θ are the toroidal coordinates, and q is the safety factor. The magnetic moment μ and the particle kinetic energy E are the two first adiabatic invariants and appear as parameters.

The Vlasov equation reads, with the subscript $s = i,e,z$ indicating the species considered (main ion, electron, or impurity)

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

The gyro-bounce-averaging operator is approximated as

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

The quasi-neutrality equation reads

$$\frac{2}{\sqrt{\pi}} \frac{T_{eq,i}}{T_0} \sum_s \left(Z_s C_s \int_0^\infty J_{0,s} f_s E^{1/2} dE\right) = C_{ad} \left(\phi - \varepsilon_\phi < \phi >_\alpha\right) - C_{pol} \sum_s C_s \tau_s Z_s^2 \Delta_s \phi$$

where $C_s = n_s/n_{eq}$ is the concentration (n_s is the population density, $n_{eq} = n_{0,e}$ is the equilibrium density, and we have $\sum_s Z_s n_s = 0$), $C_{pol} = e\omega_0 L_\psi / T_0$, $C_{ad} = C_{pol} \frac{1-f_T}{f_T} \sum_s (Z_s^2 C_s \tau_s)$ where f_T is the fraction of trapped particles and $\tau_s = T_{eq,i}/T_s$. The operator Δ_s is defined as $\Delta_s = \left(\frac{q\rho_{c0,s}}{a}\right)^2 \partial_\alpha^2 + \delta_{b,0}^2 \partial_\psi^2$ and $\varepsilon_\phi = (\sum_s \tau_s C_s Z_s^2 \varepsilon_{\phi,s}) / (\sum_s \tau_s C_s Z_s^2)$. ε_ϕ is a control parameter which governs the response of the adiabatic passing particles.

Linear theory - Influence of the radial gradient

Let us look at the influence of a radial density gradient of impurities [6]. For this study, the impurity profile is varied and the quasi-neutrality constraint is ensured. A relative impurity gradient length is defined as $G_Z = \kappa_{n_z}/\kappa_{n_i}$. The parameters of the simulations shown in this section are displayed in Table 1. It should be noted that κ_{n_i} will remain constant in the rest of the paper and equal to 0.05.

Table 1: Typical plasma parameters used.

ρ_{c_e}	ρ_{c_i}	ρ_{c_z}	δ_{b_e}	δ_{b_i}	δ_{b_z}	$\kappa_{T,s}$	$\tau_{e,z}$	κ_{n_i}	C_i	C_z	C_e
0.01	0.03	0.0072	0.01	0.1	0.024	0.25	1	0.05	0.968	0.0008	1

We show two cases in Fig. 1, corresponding to a population of tungsten impurities ($Z_z = 40$) with the same concentration, but opposite gradients $G_Z = \pm 20$. Note that this value is large mainly because $\kappa_{n,i}$ is small. In that situation, the linear analysis shows that for an impurity profile peaked ($G_Z > 0$) the TEMs are the most linearly unstable (see Fig. 1(a)). On the other hand, when the impurity profile is hollow ($G_Z < 0$), the TIMs are the most linearly unstable but dominant only in the low mode range, while TEMs are dominant beyond $n = 10$ and stay unstable even when TIMs are stable (see Fig. 1(b)).

We observe that the gradient of heavy impurities, when it is in the same direction as the main ion species gradient, will decrease the TIM growth rate and increase the TEM growth rate, whereas it will increase the TIM growth rate and decrease the TEM growth rate when these gradients are in opposing directions.

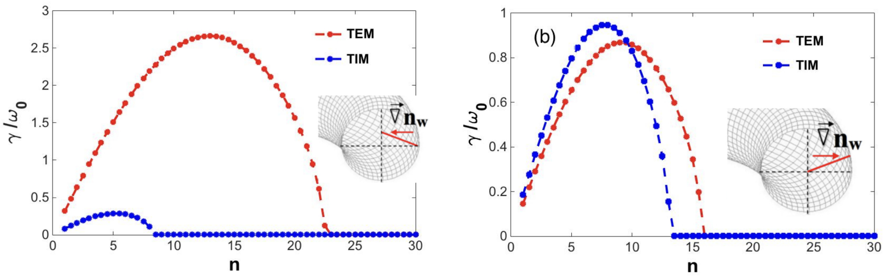

Figure 1: *Growth rate of TEMs and TIMs as a function of mode number. Case (a):* $G_Z = +20$, *case (b):* $G_Z = -20$.

Nonlinear simulations - Impurity transport

In this section, we will investigate the transport of particles when impurities are present [6]. The particle flux is defined as [7]

$$\Gamma_s = -\frac{2}{\sqrt{\pi}} \int d\alpha \int \frac{\partial J_{0,s}\phi}{\partial \alpha} f_s E^{\frac{1}{2}} dE \tag{1}$$

The impurity particle flux can be modeled as the sum of a diffusive flux and a convective flux

$$\Gamma_Z = -D\nabla n_z + V n_z \tag{2}$$

where D is a diffusion coefficient and V is a pinch velocity.

Fig. 2 shows the impurity particle flux Γ_Z, averaged over the spatial variables, and averaged over time, as a function of G_Z. We see that there are different transport regimes depending on the radial impurity density gradient.

Let us first look at the range $-20 < G_Z < -15$. This is a range of parameters where the TIMs dominate the dynamics, and we can see that there is a weak dependence of the transport on the impurity density gradient. In the next range, $-15 < G_Z < -12$, there is a competition between TIMs and TEMs, and we can observe a strong decrease of the transport with a small increase of the gradient. This is likely due to a transition from the ion driven to the electron driven turbulent regime. This leads to a range $-12 < G_Z < +6$ where the particle flux scales close to linearly, but there is a change of transport coefficient depending on the sign of G_Z, with a transport coefficient in the peaked profile larger than in the hollow profile. However, the transition from inward to outward transport occurs very close to $G_Z = 0$, which indicates that in that turbulent regime, the pinch effect is negligible compared to the turbulent transport.

Then in the range $+6 < G_Z < +20$, the transport increases with a rate faster than linear with respect to G_Z. To provide a basic explanation of this change of slope, we also estimate the flux

$\frac{\Gamma_Z}{n_e C_z}$. We assume that the pinch velocity is zero, that n_e and κ_{n_i} are constant. The flux is thus proportional to $-DG_Z$. Using the mixing length estimate, we assume that the diffusion coefficient is equal to γ/k_r^2, with k_r constant and γ being linear growth rates of the TEM instability as a function of G_Z. This estimated flux is also plotted against G_Z in Fig. 2 (in red, dotted line). We observe a qualitative agreement between the flux obtained from nonlinear TERESA simulations and that of given by the mixing length estimate.

Conclusion

We have studied the impact of the presence of a population of impurities in a tokamak plasma using the gyrokinetic code TERESA. We have shown that their presence can have a strong influence on the dynamics of the turbulence in the plasma. In particular, it was shown that the direction of the radial gradient of impurities could change the nature of turbulence. Moreover, it appears that the transport of impurities in the case of TEM turbulence and for this set of parameters is in agreement with the mixing length estimate. In light of these results, it is clear that it is very important when looking at the dynamics of impurities to treat them self-consistently, as their effect on the turbulence can strongly affect their transport.

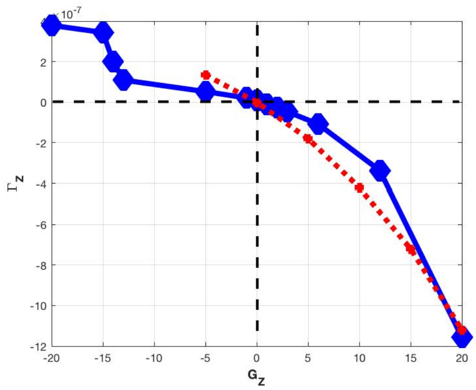

Figure 2: *Averaged impurity flux Γ_Z as a function of G_Z. The dots correspond to simulation points (in blue). In red (dotted line) is shown the particle flux estimated from the mixing length estimate ($\Gamma_Z \propto -\gamma G_Z$) and using the linear growth rates of the TEM instability as a function of G_Z.*

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