Influence of RF Fields on Anomalous Impurity Transport in Tokamaks

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Abstract. Trace impurity transport in tokamaks is studied using an electrostatic, collisionless fluid model for Ion-Temperature-Gradient (ITG) and Trapped-Electron (TE) mode driven turbulence in the presence of radio frequency (rf) fields in the ion cyclotron range of frequencies, and the results are compared with neoclassical predictions. Two separate effects of the rf field on ITG/TE-mode stability and impurity transport are considered, namely an incoherent interaction between a fast magnetosonic source wave and ITG modes; and the ponderomotive force associated with the rf field of the fast magnetosonic wave. It is shown that the trace impurity transport can be affected by the rf fields. However, the impurity diffusivity and convective velocity (pinch) are usually similarly affected and hence the steady state impurity density peaking factor $-\nabla n_z/n_z$ is only moderately affected by the rf fields.

1. **Introduction**

Impurities may have a significant effect on tokamak performance by their contribution to radiation losses and plasma dilution. Recent experiments have shown that auxiliary heating can influence impurity accumulation in tokamaks. In particular, it has been observed that accumulation of high-Z impurities can be avoided with the injection of radio-frequency (rf) power if most of the heating power is deposited on the electrons, while if the heating is deposited on the ions, the impurities accumulate in the center [1-4]. In the present study the transport of impurities by ITG and TE mode turbulence in the presence of rf fields in the ion cyclotron range of frequencies (ICRF) is investigated using an electrostatic, collisionless fluid model [5]. The trace impurity diffusivity and convective velocity (pinch) are calculated with contributions from ∇T_z (thermodiffusive flux), curvature and parallel impurity compression.

Two separate effects of the rf field on ITG/TE-mode stability and impurity transport are considered, based on a) the ponderomotive force associated with the gradient of the rf field of the fast magnetosonic wave, and b) an incoherent interaction between a fast magnetosonic source wave and ITG modes. Earlier work has shown that the ponderomotive force may influence the s-α stability diagram for ballooning modes [6] and that the parametric interaction between ITG modes and ICRF waves may influence ITG stability [7]. However, the parametric interaction is a coherent process whereas the interaction in real situations is expected to be incoherent. Therefore, we here focus on the effects on the impurity transport resulting from the incoherent interaction between ITG modes and ICRF fields and on the influence of the ponderomotive force, and the results are compared with neoclassical predictions.

2. Formulation

To describe the background ITG/TE mode turbulence, a set of fluid equations [5] is used for the particle density n, parallel velocity $v_\parallel$ and temperature T, in the presence of rf fields. The collisionless electrostatic limit is considered, and the free electrons are assumed to be Boltzmann distributed. The ion and electron perturbations are calculated and then coupled through the quasineutrality condition $\delta n_i/n_i = f_t\ \delta n_{et}/n_{et} + (1-f_t)\ \delta n_{ef}/n_{ef}$, where f_t is the fraction of trapped electrons. A semilocal analysis [8-9] is used where the eigenvalue equation is reduced to a set of coupled algebraic equations by assuming a strongly ballooning eigenfunction ($\phi = 1/\sqrt{3\pi}(1+\cos\theta), |\theta| < \pi$).

First, the modelling of the rf ponderomotive force is described. The radial rf ponderomotive force enters the equations through an additional poloidal ion drift $\vec{v}_{i-RF}$ (see [10] for details). The effect can be expressed through the normalized drift frequency $\overline{\Omega}_{z-RF} = \left(R/2Zc_z^2\right)\partial\left\langle\tilde{v}_{z-RF}\right\rangle^2/\partial r$ where $\tilde{v}_{z-RF}$ is the radial impurity velocity perturbation at the ICRF wave scale, <…> is the average over the fast ion cyclotron time scale, and $c_z = \sqrt{T_z/m_Z}$. In the treatment of the ion drift due to the ponderomotive force, the compression effect fulfills $\nabla\cdot(\vec{v}_{i-RF}) << \vec{v}_{i-RF}\cdot\nabla$ and has been omitted. The main effect of the ponderomotive force ($\vec{k}\cdot\vec{v}_{i-RF}$) is then to shift the real frequency of the ITG mode. This frequency shift can significantly modify the phase relation between the impurity density and potential perturbations and hence affect the impurity flux.

Next, we examine an incoherent interaction of rf waves in Ion cyclotron/Ion Bernstein wave (IBW) range of frequencies ($\omega \approx \Omega_i$) with the toroidal η_i-mode, an interaction which indirectly can affect the impurity transport. Earlier work [7] has studied the coherent parametric interaction between rf waves and the toroidal η_i- mode but in real situations the interaction is expected to be incoherent due to the presence of broadband rf noise. We assume that there is a sufficient spectral gap between the η_i-mode ($\omega,\vec{k}$) and rf ($\omega_0,\vec{k}_0$) turbulences. The slow η_i-mode is affected by the quadratic nonlinearity due to the interaction of rf waves via Reynolds stress. The response of the rf wave due to η_i-mode turbulence can be obtained from the wave kinetic equation (WKE) [11]. The effective Doppler shift and modulated frequency of the rf wave from a slowly varying perturbation in WKE are given by $\delta\omega_k \approx k_{0\perp}\delta V_E - 0.25k_{0\perp}^2 c_i^2(\delta T_i/T_i)(1-0.5k_{0\perp}^2 c_i^2)^{-1}$. Here the linear dispersion relation for the IBW above the lower hybrid cut off is $\omega^2 \approx 4\Omega_i^2 - 3k_{0\perp}^2 c_i^2$.

The rf effects enter in the ion continuity equation through Reynolds stress (or polarization nonlinearity). Using the response of the rf wave to the ITG mode from the WKE in the ion continuity equation, we get

$$\left(\omega+\tau_i\varepsilon_n\omega_*\right)\tilde{n}_k + \left(\tau_i\varepsilon_n\omega_* - i\sigma_T\right)\tilde{T}_k - \left(\omega_* - \varepsilon_n\omega_* + i\sigma_\phi\right)\tilde{\phi}_k + k_\perp^2\rho_s^2\left(\omega+\tau_i(1+\eta_i)\omega_*\right)\tilde{\phi}_k = 0 \qquad (1)$$

Here $\sigma_T = \dfrac{2c_s}{L_n} k_x \rho_s k_y \rho_s \dfrac{k_{0\perp}^2 \rho_s^2}{4} \dfrac{\Omega_i^2}{\Omega_i^2 - \omega_{k0}^2} \left| \dfrac{e\phi_{ko}}{T_e} \right|_{RF}^2$; $\sigma_\phi = \dfrac{4\omega_{k0}\Omega_i}{\Omega_i^2 - \omega_{k0}^2} \sigma_T$ (2)

Here $\tilde{\phi}_k = e\phi_k / T_e$, $\tilde{n}_k = \delta n_k / n$ and $\tilde{T}_k = \delta T_k / T$ are the normalised potential, ion density and ion temperature perturbations, ω and k are the eigenvalue and wavevector of the unstable ITG/TE modes, $\tau_i = T_i/T_e$, $\varepsilon_n = 2L_n/R$, $\rho_s = c_s / \Omega_{ci}$ and $c_s = \sqrt{T_e / m_i}$. The rf effects enter through the parameters σ_T and σ_ϕ where ϕ_{k0} is the potential associated with the IBW.

The trace impurity species is described by the same set of fluid equations [9] as the main ions (but neglecting effects of finite impurity Larmor radius), including effects of the parallel impurity compression. For $T_i / T_e \approx T_z / T_e \approx 1$, the ratio of the radial ponderomotive force experienced by the ion and impurity species is $\overline{\Omega}_{i-RF} / \overline{\Omega}_{z-RF} \approx Z$ since the rf velocity field oscillations in the ion and impurity fluid are typically $\tilde{v}_{i-RF} \approx c_s$ and $\tilde{v}_{z-RF} \approx c_{sz}$ respectively. Thus, we can neglect the radial ponderomotive effects in the impurity dynamics for $Z >> 1$. From the impurity density response $\tilde{n}_z$, the quasilinear impurity particle flux can be calculated as

$$\Gamma_{nz} = -n_z \rho_s c_s \left\langle \tilde{n}_z \frac{\partial \tilde{\phi}}{r\partial\theta} \right\rangle = -D_z \nabla n_z + n_z V_z \quad (3)$$

where D_z and V_z are the impurity diffusivity and convective velocity respectively, where the first term is the diffusive flux and the second term represents the impurity convective velocity with contributions from ∇T_z (thermodiffusive flux), curvature and parallel impurity compression.

3. Results

a) Effects of the rf ponderomotive force

The quasilinear impurity particle flux is calculated for a fixed length scale of the turbulence with $k_\perp^2 \rho_\perp^2 = 0.1$, and with a modified mixing length potential fluctuation level [5]. In Fig. 1 the impurity diffusion coefficient D_z, convective velocity RV_z (in units of $2\rho_s^2 c_s/R$) and impurity density peaking factor $-RV_z/D_z$ of a trace impurity species as a function of the rf ponderomotive force term $\overline{\Omega}_{i-RF}$ are shown. The parameters are $R/L_{Ti} = R/L_{Tz} = R/L_{Te} = 7$ (where $R/L_j = -R dj/dr/j$), Z=6, $f_t = 0.5$, q=1.4 is the safety factor, s=0.8 is the magnetic shear, $T_e/T_{i,z} = 1$ and $R/L_{ne} = 3$. For these parameters, the ITG mode is the dominant instability. For $\overline{\Omega}_{i-RF} < 0$ (corresponding to a situation with $d|E_\perp|^2/dr < 0$) and $\overline{\Omega}_{i-RF} > 2$, a significant reduction of the inward impurity velocity $|V_z|$ is obtained. Transiently, this could lead to a reversal of the impurity flux, from inward to outward. However, since the ponderomotive force affects D_z and V_z in a similar way, the steady state impurity density peaking factor $-V_z/D_z$ does not seem to be as strongly affected by the rf field as indicated by recent tokamak experiments [1].

Adding neoclassical transport will not affect the peaking factor significantly, since the effect of neoclassical processes on diffusion is negligible and the neoclassical convective velocity (for the above parameters) is smaller than the turbulent one. For the parameters of Fig. 1, the inward neoclassical flow due to the ion density gradient is larger than the temperature screening induced by the ion temperature gradient, and therefore the total neoclassical flow is inward. Assuming large aspect ratio, circular cross section plasma, and JET-like parameters ($n_e=5\cdot10^{19}$ m^{-3}, $T_i=T_z=10$ keV, $n_z/n_e=0.01$, r=0.5 m, and R=3 m), the neoclassical diffusion constant D_z^{neo} and convective velocity V_z^{neo} defined as $\Gamma_z^{neo}=-D_z^{neo}\nabla n_z+n_zV_z^{neo}$ are $D_z^{neo}=0.002$ and $RV_z^{neo}=-0.34$ (in units of $2\rho_s^2c_s/R$). Here we have assumed that both the impurities and main ions are collisionless and used Eq.(14) of [9] to calculate Γ_z^{neo}.

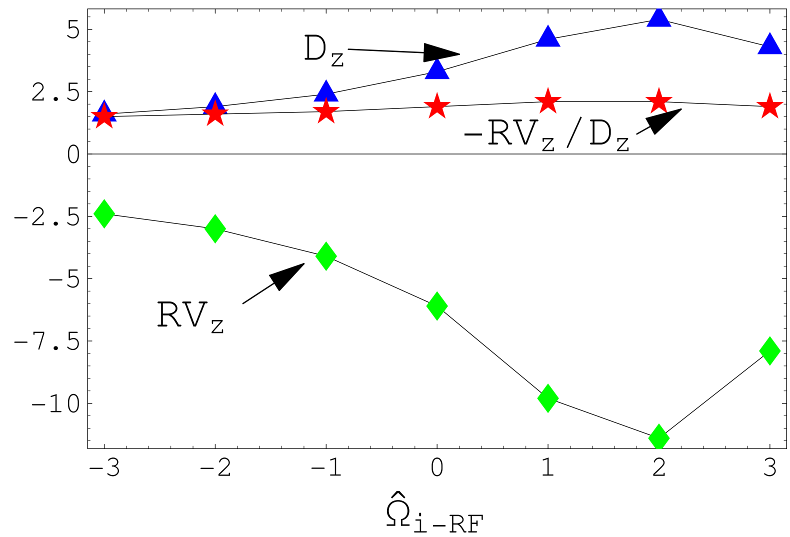

Fig. 1. Trace impurity diffusion coefficient D_z, convective velocity RV_z (in units of $2\rho_s^2c_s/R$) and normalised impurity density peaking factor $-RV_z/D_z$ as a function of the ICRF ponderomotive force term $\overline{\Omega}_{i-RF}$ for an ITG mode dominated case.

Fig. 2 shows the impurity diffusion coefficient D_z, convective velocity RV_z and impurity density peaking factor $-RV_z/D_z$ as a function of the rf ponderomotive force term $\overline{\Omega}_{i-RF}$ for a TE mode dominated case. The other parameters are $R/L_{Te}=7$, $R/L_{Ti,z}=0$, Z=6, $f_t=0.5$, q=1.4, s=0.8, $T_e/T_{i,z}=1$ and $R/L_{ne}=3$. As observed, the impurity peaking factor is smaller for the TE mode dominated case. This difference is mainly a result of the parallel impurity compression term which contributes to an outward impurity convective velocity for TE modes [12]. In this case, also the impurity peaking factor is slightly reduced in the presence of the rf field.

As in the ITG-dominated case, the neoclassical diffusion coefficient is negligibly small, but the neoclassical convective velocity can dominate over the anomalous convective velocity for large $\overline{\Omega}_{i-RF}$. Assuming the same JET-like parameters as in the previous case, the neoclassical convective velocity is now $RV_z^{neo}=-0.67$ (in units of $2\rho_s^2c_s/R$). In this case the ion temperature gradient is zero, so the outward flow that would be induced by it is zero. The neoclassical flow is driven by the ion density gradient and it is inward.

The scalings of the impurity transport with normalised temperature- and density gradients, impurity charge Z and other plasma parameters are discussed in Refs. [9-10,12-13].

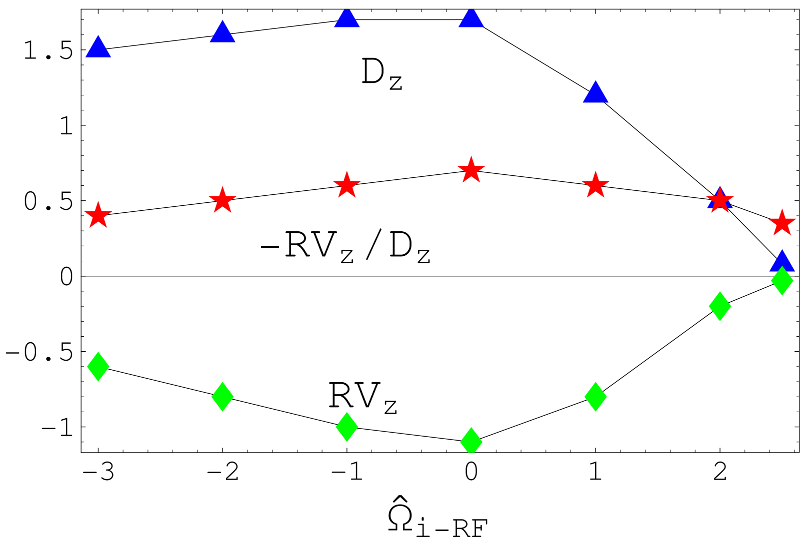

Fig. 2. Trace impurity diffusion coefficient D_z, impurity convective velocity RV_z (in units of $2\rho_s^2c_s/R$) and normalized impurity density peaking factor $-RV_z/D_z$ as a function of the ICRF ponderomotive force term $\overline{\Omega}_{i-RF}$ for a TE mode dominated case.

b) Effects of the incoherent interaction of ITG modes with rf waves

The non-linear dispersion relation for ITG modes (Eq. 1) is solved for pure ITG modes (i.e, neglecting electron trapping) in the presence of an ICRF field with amplitude ϕ_{k0}. The amplitude of the rf field enters the non-linear dispersion relation through the parameters σ_T and σ_ϕ and we here assume that $\sigma_T=\sigma_\phi=\sigma$ where the parameter σ is varied as $0<\sigma<1$.

Fig. 3 shows the scaling of the impurity diffusion coefficient D_z, convective velocity RV_z and impurity density peaking factor $-RV_z/D_z$ as a function of σ for $f_t=0$ and with the other parameters as in Fig. 1 with $R/L_{Tj}=7$, $Z=6$, $q=1.4$, $s=0.8$, $T_e/T_{i,z}=1$ and $R/L_{ne}=3$. The rf interaction results in a destabilisation of the ITG mode and an increase of both the impurity diffusivity and the inward impurity convective velocity. However, the impurity peaking factor is very weakly affected by the rf field, in line with the results obtained for the ponderomotive force.

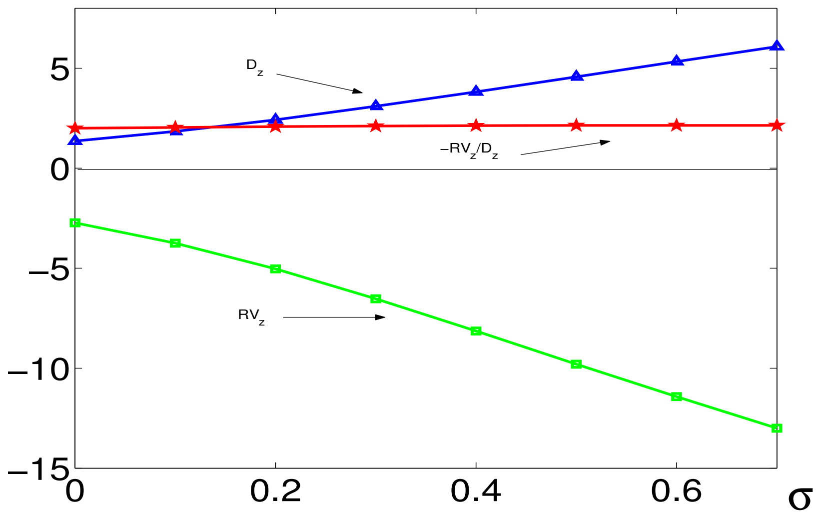

Fig. 3. Trace impurity diffusion coefficient D_z, impurity convective velocity RV_z (in units of $2\rho_s^2 c_s/R$) and normalized impurity density peaking factor $-RV_z/D_z$ as a function of the ICRF interaction term σ for f_t=0 and with the other parameters as in Fig. 1 with R/L_{Tj}=7, Z=6, q=1.4, s=0.8, $T_e/T_{i,z}$=1 and R/L_{ne}=3.

4. Conclusions

In conclusion, we have studied trace impurity transport in tokamaks due to ITG/TE mode turbulence including two separate effects of an applied ICRF field, i.e. the ponderomotive force associated with the gradient of the rf field and an incoherent interaction between the rf source waves and ITG modes. The results show that the ITG/TEM eigenvalues and hence the trace impurity particle transport can be affected by the ICRF fields. The effect is expected to be strongest close to the rf resonance location and is seen for both ITG and TEM dominated plasmas. However, the impurity diffusivity and convective velocity are usually similarly affected by the rf fields and consequently the steady state impurity density peaking factor $-\nabla n_z/n_z = -V_z/D_z$ is only weakly affected. The size of the anomalous convection is larger than the neoclassical for typical tokamak parameters, but if the anomalous convection is reduced by the rf-field, the neoclassical contribution may be dominant and this may modify the impurity density peaking factor.

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