Anomalous Impurity Transport in Tokamaks in the Presence of RF Fields

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Abstract

Recent experiments[1-4] have shown that auxiliary heating can influence impurity accumulation in Tokamaks. In the present study the transport of impurities by Ion-Temperature-Gradient (ITG) and Trapped-Electron (TE) mode turbulence in the presence of radio frequency (rf) fields in the ion cyclotron range of frequencies is investigated using an electrostatic, collisionless fluid model. The turbulence is affected by the ponderomotive force associated with the rf field of the fast magnetosonic wave in the plasma. It is shown that the inward impurity convective velocity (pinch) and diffusivity can be reduced by the rf field, in particular close to the wave resonance location where the ponderomotive force may be significant. However, the steady state impurity density peaking factor $-\nabla n_z/n_z$ does not seem to be as strongly affected by the rf field as indicated by recent tokamak experiments.

To describe the background ITG/TE turbulence in the presence of an rf ponderomotive force, a set of fluid equations[5] is used:

$$\frac{\partial n_j}{\partial t} + \nabla \cdot \left(n_j \vec{v}_j \right) = 0 \qquad (1)$$

$$m_i n_i \frac{\partial \vec{v}_{\parallel i}}{\partial t} + \nabla_\parallel p_i + n_i e \nabla_\parallel \phi = 0 \qquad (2)$$

$$\frac{3}{2} n_j \frac{dT_j}{dt} + n_j T_j \nabla \cdot \vec{v}_j + \nabla \cdot \vec{q}_j = 0 \qquad (3)$$

where j=i, et represent ions and trapped electrons, m_i is the ion mass, ϕ is the electrostatic potential, and the perpendicular velocity is $\vec{v}_\perp = \vec{v}_E + \vec{v}_* + \vec{v}_p + \vec{v}_\pi + \vec{v}_{i-RF}$ where $\vec{v}_E$ is the ExB drift, $\vec{v}_*$ is the diamagnetic drift, $\vec{v}_p$ is the polarization drift, $\vec{v}_\pi$ is the stress tensor drift and $\vec{q}$ is the diamagnetic heat flux. Here, $\vec{v}_{i-RF} = (1/2\Omega_i)d/dr\langle\tilde{v}_{rf}\rangle^2$ is an additional poloidal ion drift due to the radial rf ponderomotive force, where Ω_i is the ion cyclotron frequency, $\tilde{v}_{rf}$ is the velocity perturbation at the rf wave scale, and <…> is an average over the fast ion cyclotron time scale. In Eqs. (1-3), the collisionless electrostatic limit is considered, and the free electrons are assumed to be adiabatic. The ion and electron perturbations are 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. The eigenvalue equation is reduced to a set of coupled algebraic equations by assuming a strongly ballooning eigenfunction[6] $(\phi = 1/\sqrt{3\pi}(1+\cos\theta), |\theta| < \pi)$. The compression of the ion drift due to the ponderomotive force fulfills $\nabla\cdot(\vec{v}_{i-RF}) \ll \vec{v}_{i-RF}\cdot\nabla$ and has been omitted and hence the main effect of the ponderomotive force is a shift in the real frequency of the ITG mode ($\vec{k}\cdot\vec{v}_{i-RF}$). The ponderomotive force has been estimated with data taken from simulations of ion cyclotron radio frequency (ICRF) heating scenarios where strong gradients of the wave field amplitude are expected in the vicinity of the resonance location. In particular, the wave field has been simulated with the EVE code[7] for hydrogen minority heating, (H)D, using parameters typical of the JET tokamak.

The trace impurity species is described by the same set of fluid equations,[5,8] neglecting the effects of finite impurity Larmor radius. In addition, the radial ponderomotive force in the impurity dynamics can be neglected for Z>>1. From the impurity density response $\tilde{n}_z$, the quasilinear impurity particle flux is calculated as $\Gamma_{nz} = -n_z\rho_s c_s \left\langle \tilde{n}_z \frac{\partial\tilde{\phi}}{r\partial\theta} \right\rangle = -D_z\nabla n_z + n_z V_z$ where D_z and V_z are the impurity diffusivity and convective velocity respectively. A fixed length scale of the turbulence is used with $k_\theta^2\rho_s^2 = 0.1$ combined with a modified mixing length fluctuation level.[5]

Fig. 1 shows the trace impurity diffusion coefficient D_z, convective velocity RV_z (in units of $2\rho_s^2 c_s/R$) and normalized impurity density peaking factor $-R\nabla n_z/n_z = -RV_z/D_z$ as a function of the rf ponderomotive force term $\overline{\Omega}_{i-RF}$ (the ponderomotive force enters through a normalized drift frequency $\overline{\Omega}_{i-RF} = k\cdot\vec{v}_{i-RF}/\omega_{De} = (R/2c_i^2)\partial\langle\tilde{v}_{rf}\rangle^2/\partial r$). The parameters are $R/L_{Ti}=R/L_{Tz}=R/L_{Te}=7$ (where $R/L_j=-Rdj/dr/j$), Z=6, $f_t=0.5$, q=1.4, s=0.8, $T_e/T_{i,z}=1$ 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. However, since the ponderomotive force affects D_z and V_z in a similar way, the steady state impurity density peaking factor $-RV_z/D_z$ is not strongly affected by the rf field.

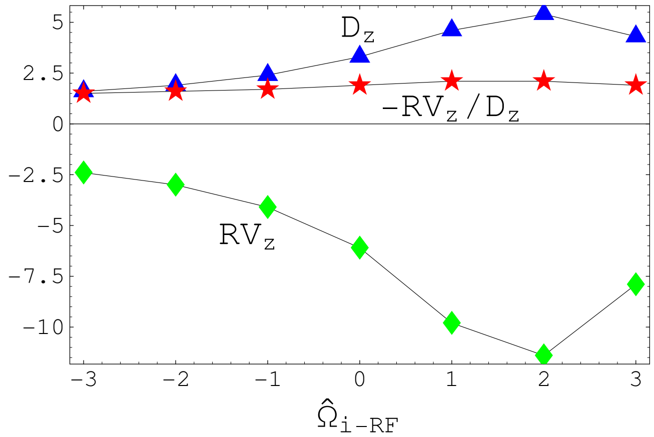

Fig. 1. D_z, RV_z (in units of $2\rho_s^2c_s/R$) and impurity density peaking factor $-RV_z/D_z$ as a function of the rf ponderomotive force term $\overline{\Omega}_{i-RF}$ for an ITG mode dominated case.

Fig. 2 shows the same scalings for a TE mode dominated case. Here, the 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 $R/L_{ne}=3$. We note that 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.[9] We have verified that these results, in particular for the peaking factor $-RV_z/D_z$, are rather insensitive to variations in other plasma parameters.

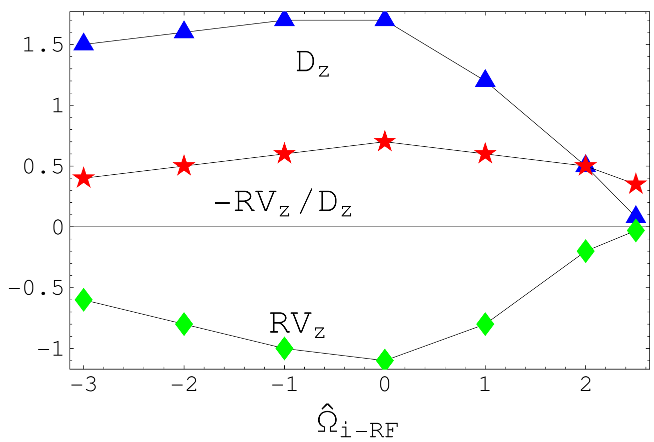

Fig. 2. The same scalings as in Fig. 1 for a TE mode dominated case.

In conclusion, trace impurity transport driven by ITG/TE mode turbulence including effects of the ponderomotive force due to an applied ICRF field were studied using the Weiland fluid model for ions, trace impurities and deeply trapped electrons. The results show that the usual inward impurity convective velocity (impurity pinch) and diffusivity can be reduced by the ponderomotive force. However, the density peaking factor $-\nabla n_z/n_z = -V_z/D_z$ is only moderately affected by the rf field.

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REFERENCES

1. M. E. Puiatti, M. Valisa, C. Angioni, et al, Phys. Plasmas 13, 042501 (2006).
2. L. Carraro, C. Angioni, C. Giroud, et al, Proceedings of 34th EPS Conference on Controlled Fusion and Plasma Physics, Warszawa 2007, Vol. 31 A.
3. C. Giroud, C. Angioni, L. Carraro, et al, Proceedings of 34th EPS Conference on Controlled Fusion and Plasma Physics, Warszawa 2007, Vol. 31 F, P-2.049.
4. S. Günter, C. Angioni, M. Apostoliceanu, et al, Nucl. Fusion 45, S98 (2005).
5. J. Weiland, "Collective modes in inhomogeneous plasma", (IOP Bristol, 2000).
6. A. Hirose, Phys. Fluids B5, 230 (1993).
7. R.J. Dumont and L.-G. Eriksson, in {Theory of Fusion Plasmas}, Proceedings of the Joint Varenna-Lausanne International Workshop, Varenna, Italy, 2006 (AIP, Melville, New York, 2006), p. 65.
8. H. Nordman, T. Fülöp, J. Candy, P. Strand and J. Weiland, Phys. Plasmas 14, 052303 (2007).
9. C. Angioni, A. G. Peeters, Phys. Rev. Lett. 96, 095003-1 (2006).