Turbulent Particle Transport in ITER H-mode Scenario

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Introduction

Understanding the physics processes determining particle transport in burning plasmas is a key issue, since the fuel and impurity density profiles have a significant influence on fusion performance. Particle transport is predicted by the theory of collisional transport, but the predictions of neoclassical theory are rarely matched by observations. Turbulent transport is considered as a plausible candidate for explaining this discrepancy.

Turbulent transport of tritium, deuterium, and impurities in the ITER H-mode scenario has been investigated with a three dimensional global fluid code (TRB) [1], which allows us to study ion temperature gradient (ITG) and trapped electron mode (TEM) driven turbulence in tokamak plasmas. These simulations are consistent with the predictions of the quasi-linear theory.

The ITER tokamak will rely on α-particle heating, neutral beam injection, ion cyclotron radiofrequency heating (ICRF), and electron cyclotron resonance heating (ECRH). In contrast to most current experiments, ITER will have predominant electron heating. This is expected to have a strong influence on the particle transport. In order to address this issue, the variation of the turbulent particle fluxes with the ratio of electron to ion heating been investigated using the TRB code. The simulation results show that the effect of electron heating on the transport of tritium (in trace approximation) and of impurities is opposite. Increasing the electron heating causes the tritium profile to become less hollow while it decreases slightly the impurity density peaking. This scenario is favourable for improving the DT reaction rate in burning plasmas with trace tritium. The paper will provide details of the turbulence model and the range of plasma parameters investigated together with predictions for the profiles of fuel and impurity ions in ITER H-mode plasmas.

Model Equations

In collisionless plasmas, in the range of scales larger than an ion gyroradius ($k_\perp \rho_i < 1$), the main instabilities are the ion temperature gradient (ITG) and the collisionless trapped electron modes (TEM). ITG/TEM turbulence is studied with the TRB code. The code solves the evolution equation of density and pressure for three species: ions, trapped electrons, and one impurity species. A set of fluid equations is used here to describe a collisionless ITG/TEM turbulence:

$$d_t n_s = -\kappa_s \cdot (n_s \nabla\phi + \nabla p_s/e_s) - \nabla_\parallel \left(n_s v_{\parallel s}\right). \quad (1)$$

$$d_t p_s = -\kappa_s \cdot \left(p_s \nabla\phi + \nabla\left(p_s^2/n_s\right)/e_s\right) - \gamma\nabla_\parallel\left(p_s v_{\parallel s}\right), \quad (2)$$

$$n_s m_s d_t v_{\parallel s} = -n_s e_s \nabla_\parallel \phi - \nabla_\parallel p_s. \quad (3)$$

Here, n_s, p_s, $v_{\parallel s}$, ϕ are the density, pressure, parallel velocity, and the electric potential, respectively. The labels "s" can be "e", "i" and "z" which are for trapped electrons, ions, and impurities, respectively. We solve eight equations for n_e, n_z, p_e, p_i, p_z, Ω, $v_{\parallel i}$ and $v_{\parallel z}$. Passing electrons are assumed to be adiabatic, while the dynamics of trapped electrons is described by Eqs. (1)-(3), with zero parallel electron velocity. The continuity equation for the main ion density n_i is taken into account in a different form: from the ambipolarity relation, one gets instead an equation for the the vorticity Ω, $\Omega = f_c n_{e,eq} \frac{\phi - \langle\phi\rangle}{T_{e,eq}} - \left(n_{i,eq} + A n_{z,eq}\right)\nabla^2\phi$. The curvature drift operator is $\kappa_s = \frac{2}{B}\frac{B}{B} \times \frac{\nabla B}{B}$ for ion species. For trapped electrons, κ_s is replaced by the precession frequency in the toroidal direction, i.e. $\kappa_s = \frac{1}{BR}(\frac{1}{2} + \frac{4s}{3})e_\varphi$, where, e_φ is a unit vector of toroidal direction and R is the plasma major radius. Here, $s = (r/q)dq/dr$ is the magnetic shear and $\varepsilon_a = a/R$ parametrizes the curvature ($\varepsilon_a < 1$). The Lagrangian time derivative is defined as $\frac{d}{dt} = \frac{\partial}{\partial t} + v_E \cdot \nabla - D\nabla^2$, where D is a "collisional" diffusion operator and $v_E = \frac{B \times \nabla\phi}{B^2}$ is the

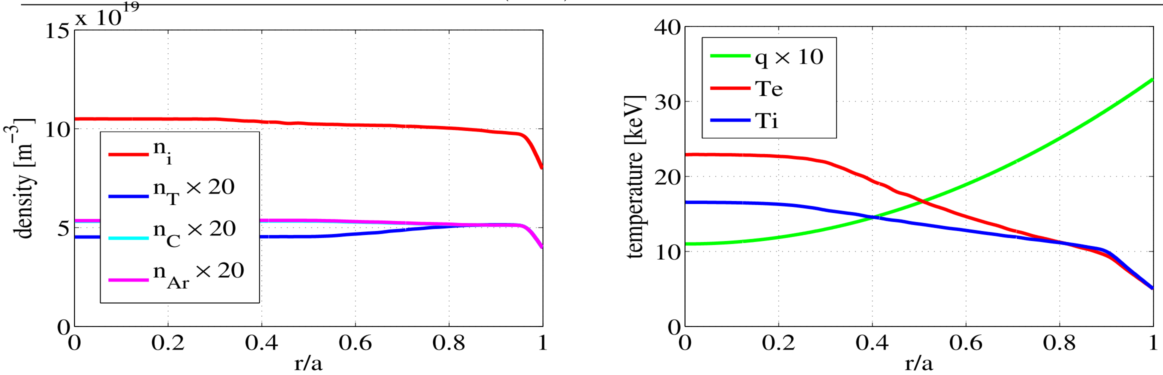

Figure 1: Radial profiles of (left) the density of deuterium, tritons, and impurities, and (right) electron temperature, ion temperature, and q-profile.

electric drift velocity. Note that the perturbed part of $f_t n_e$ is the fluctuating density of trapped electrons, whereas $n_{e,eq}$ is the total equilibrium electron density normalized to n_0. The adiabatic compression index is $\gamma = 5/3$. The normalization is of the gyroBohm type, as referenced in Ref.[2]. The fraction of trapped (respectively, passing) electrons is $f_t = 2/\pi(2r/R)^{1/2}$ (respectively, $f_c = 1 - f_t$).

Study of Particle Transport

The radial profiles of the density of ion, tritium, impurities (carbon and argon), electron temperature, ion temperature, and the q-profiles are plotted in Fig. 1. The boundary condition is given for the density $n_i = 8 \times 10^{19}\ m^{-3}$ and ion and electron temperatures $T_i = T_e = 5$ keV at the pedestal. The density and impurities show flat profiles in the core region $r/a = 0 \sim 0.9$ with values of $n_i \sim 1.1 \times 10^{20}\ m^{-3}$ for main ions and $n_z \sim 2.5 \times 10^{18}\ m^{-3}$ (it is about 2 percent of the main ion density) while the tritium shows a slightly hollow profile.

The steady state particle flux Γ_s is a sum of a diffusive term and a convective term: $\Gamma_s = -D_s \nabla n_s + n_s V_s$, where D_s is the diffusivity, n_s is the density, and V_s is the radial pinch velocity of species “s”. In steady state conditions and in the plasma regions where the source can be neglected, the local logarithmic density gradient of any species of “s” $1/L_{n_s} = -\nabla n_s/n_s$ is directly related to the ratio of the convection velocity to the diffusion coefficient, V_s/D_s. Hence, the peaking of density of species “s” is determined by the ratio $-V_s/D_s$, or equivalently the normalized peaking factor $-aV_s/D_s$. The deuterium and tritium transport is assumed to be dominated by turbulence. However, impurity transport needs to take into account neoclassical transport as thus could be comparable to turbulent transport for high Z impurities. Regarding turbulent particle transport, several mechanisms have been identified in the framework of the quasilinear theory to explain the pinch velocity. First, perpendicular compressibility induces a curvature pinch velocity which is usually directed inward but can change sign with the diamagnetic drift frequency and the magnetic shear. Second, parallel compressibility is responsible for a second contribution that depends on the phase velocity of the fluctuations. And finally, the temperature gradient is responsible for a thermodiffusion term which also depends on the phase velocity. Consequently, the collisional and turbulent impurity fluxes add up to give the total flux: $\Gamma = \Gamma_{neo} + \Gamma_{turb}$. The total transport coefficients D and V will thus be the sum of their neoclassical and turbulent components. The neoclassical convective velocity V_{neo} can be written as

$$V_{neo} = D_{neo} Z \left(\frac{1}{n_i} \frac{dn_i}{dr} + H \frac{1}{T_i} \frac{dT_i}{dr} \right), \tag{4}$$

where Z is the charge number of the impurity, and the factor H ($H < 0$) is the effectiveness of the temperature screening. Consequently, in the usual case of negative main ion density and temperature gradients (i.e. flat or peaked profiles), the ion density gradient drives an inward flux (responsible for the “impurity accumulation”) while the ion temperature gradient drives an outward flux (the temperature screening effect).

We can estimate the neoclassical transport from the main ion density and temperature profile which is shown in Fig. 1. The neoclassical diffusion coefficient D_{neo} and the the temperature screening factor H is taken from the calculation for ITER conditions [4]. The peaking factor of neoclassical transport is given by $\frac{n_{core}}{n_{edge}} = \exp\left(\frac{-aV_{neo}}{D_{neo}}\right)$.

The turbulent diffusion coefficient D_{turb} and the turbulent pinch velocity V_{turb} is computed from the simulation data as shown in Fig. 2. We find that the turbulent diffusion coefficient and the pinch velocity weakly depends on charge number Z. Turbulent diffusion coefficient for carbon and argon is $D_{C,turb} \sim 2.0\ m^2/s$ and $D_{Ar,turb} \sim 2.2\ m^2/s$, respectively. Turbulent pinch velocity for carbon and argon is $V_{C,turb} \sim -0.25\ m/s$ and $V_{Ar,turb} \sim -0.28\ m/s$), respectively. Note that turbulent diffusion coefficient D_{turb} (which is $\sim 2m^2/s$) is much larger compared to D_{neo} (which is $\sim 0.005m^2/s$ for tungsten, $\sim 0.01m^2/s$ for argon and $\sim 0.05m^2/s$ for carbon). The peaking factor for total (neoclassical+turbulent) transport is given by $\frac{n_{core}}{n_{edge}} = \exp\left(-\frac{V_{neo}+V_{turb}}{D_{neo}+D_{turb}}a\right)$.

The impurity peaking for the neoclassical transport and the one of the neoclassical+turbulent transport of carbon, argon, and tungsten are shown in Fig. 3. The critical gradient length L_n which leads to a peaking of $n_{core}/n_{edge} = 3$ of the heavy impurities (Ar and W) is $L_n \sim 5m$ for neoclassical transport. The neoclassical pinch velocity increases with the charge number Z, i.e. strong peaking for tungsten ($n_{core}/n_{edge} > 5$ is found in $L_n \geq 5m$). The impurity peaking factor includes neoclassical and turbulent transport does not show a dependence of the impurity species. This is due to the turbulent transport D_{turb} and V_{turb} is much larger than D_{neo} and V_{neo}, respectively ($D_{turb} \gg D_{neo}$, $V_{turb} \gg V_{neo}$) and D_{turb} and V_{turb} do not depend on charge number Z. This is consistent with the simulation result which is shown in Fig. 1.

The effect of the electron to ion power ratio on particle transportis of particular interest, because could it be an important knob to control density peaking. Indeed, the quasilinear theory predicts the following: a) The direction of thermodiffusion changes with the sign of the average phase velocity of turbulence, which in turn reverses going from dominant electron heating (TEM dominated) to dominant ion heating (ITG dominated) turbulence [3]. b) The thermodiffusion term is inversely proportional to the charge number, and thus for impurities is smaller than trace tritium. To assess the effect of thermodiffusion, the ratio of ion to electron heating has been changed at constant ion heating source as shown in Fig. 4. The electron and ion heat sources are high enough to maintain the temperature gradient well above the instability threshold, i.e., to establish a well developed turbulence. As expected, the effect of varying S_e/S_i has little effect on impurity peaking. The thermodiffusion effect acts in the opposite way for tritons: dom-

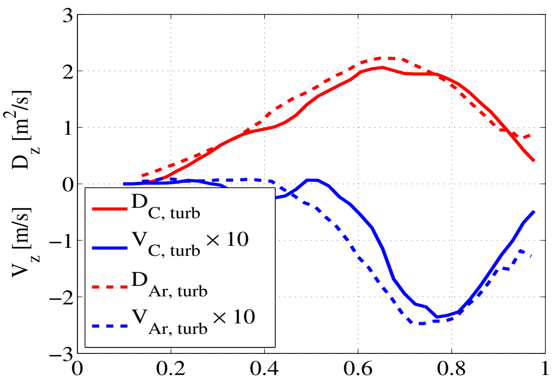

Figure 2: Radial profiles of turbulent diffusion coecient D_{turb} and turbulent pinch velocity V_{turb} of carbon (C) and argon (Ar) given by TRB simulation.

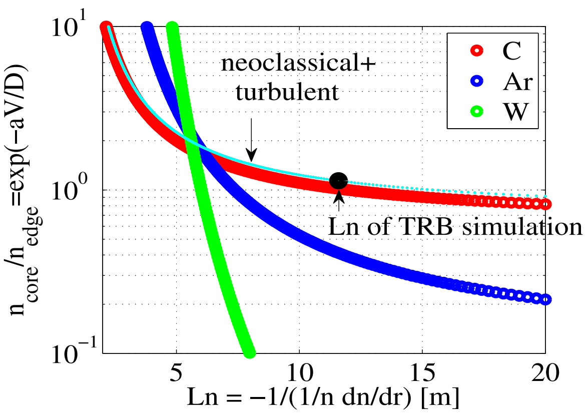

Figure 3: The dependence of the peaking factor against the gradient length of the main ion density $L_n = 1/(\frac{1}{n_i}\frac{dn_i}{dr})$.

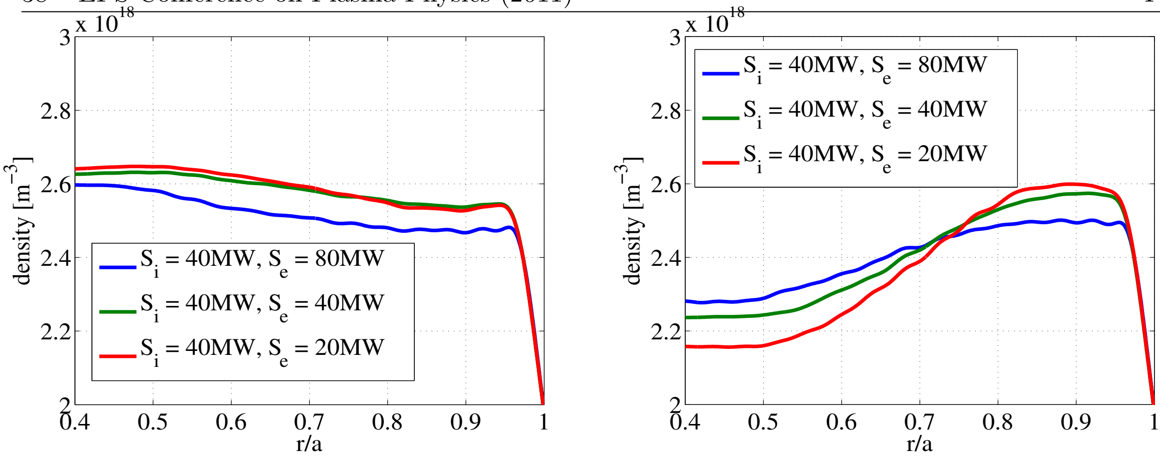

Figure 4: Effect of S_i/S_e heating ratio for (left) argon density profile and (right) tritium density profile.

inant electron heating decreases V/D ($V \geq 0$ for tritium) and thus makes the tritium profile less hollow.

Conclusion

Particle transport has been studied for ITER H-mode scenarios. This has been done by calculations of neoclassical transport and the numerical simulations of turbulent transport by a three dimensional global fluid code (TRB). The neoclassical transport is computed from the profile of ITER H-mode scenarios calculated by TRB with given pedestal boundary conditions. For the neoclassical transport, the impurity density profile peaking has a strong dependence on the charge number. However, turbulent simulations show a very weak dependence of impurity peaking on Z and very flat impurity density profiles. The effect of the electron to ion power ratio has little effect on impurity peaking as the thermodiffusion term is inversely proportional to the charge number. Thermodiffusion effect acts on the opposite way for tritons (trace approximation): dominant electron heating increases V/D for tritons thus leading to a less hollow and slightly decreases the impurity density in the core. This scenario is favourable for improving the DT reaction rate in burning plasmas with tritium.

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