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Modelling of transport and profile modifications in tokamaks with ergodic divertors

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Introduction

Significant modifications of transport properties have been observed at the plasma edge in several tokamaks [1]-[4] by stochastization of the magnetic field with ergodic divertors (ED). On the one hand, an essential increase of the particle and heat transport has been found in the very outer region where the perturbation from ED is strong enough. This is induced by the transfer along perturbed field lines inclined with respect to undisturbed magnetic surfaces. On the other hand, a region with a very steep temperature profile and reduced transport was observed in a deeper plasma zone. Such a modification is most probably provided by the reduction of the transport perpendicular to the field lines under conditions of a relatively weak stochastization. In the present work a coherent approach to model these effects from stochastization is presented. A semi-analytical model for the effective transport coefficients is developed, which includes the effects of flows both along stochastic field lines and perpendicular to them induced by the most important drift microinstabilities. These coeffcients are incorporated into the transport code RITM in order to simulate the modifications in radial profiles of plasma parameters provided by ED. Results of calculations for Tore Supra and TEXTOR are presented.

Effective transport coefficients in a stochastic magnetic field

The magnetic field perturbation from ED includes normally a broad spectrum of Fourier harmonics with different poloidal and toroidal multiplicities m and k. They generate chains of magnetic islands at the positions of the resonant magnetic surfaces with the safety factor $q = m/k$. The overlap of neighbouring island chains is characterized by the Chirikov parameter σ_{ch}, the ratio of the island width to the radial distance between adjacent resonant surfaces. If $\sigma_{ch} > 1$, the field lines are stochastized and experience chaotic displacements in the radial direction. This behaviour is described by the Kolmogorov length L_K and field line diffusivity D_{Fl} [5]. With known L_K, D_{Fl}, the heat conductivity $\kappa_\perp$ and particle diffusivity $D_\perp$ perpendicular to field lines one can estimate the effective radial transport coefficients [2, 5, 6]. Thus, according to Ref.[6], $\kappa_{eff} = \kappa_\perp \xi_{max}$ and $D_{eff} = D_\perp \psi_{max}$, with ξ_{max} and ψ_{max} being the maximum values of the functions $\xi = \frac{1+\zeta_T x \exp(-x)}{1+\zeta_T x \exp(-2x)}$, $\psi = \frac{1+\zeta_n x^2 g}{1+\zeta_n x^2 \exp(-x) g}$ of a variable x, with

$g = [1-\exp(-x)]/[\exp(3x)-1]$, $\zeta_T = 2D_{Fl}\kappa_{\parallel}/L_K\kappa_{\perp}$, $\zeta_n = 24\left(D_{Fl}c_s/D_{\perp}\right)^2$, $\kappa_{\parallel}$ being the parallel heat conductivity, $c_s = \sqrt{(T_e+T_i)/m_i}$ the ion sound velocity, $T_{e,i}$ the charged particle temperatures and m_i the ion mass.

Anomalous transport perpendicular to field lines

In order to determine the perpendicular transport coefficients $\kappa_{\perp}$ and $D_{\perp}$, we apply a quasi-linear approximation by describing typical edge drift micro-instabilities including drift-Alfvèn, drift resistive and drift resistive ballooning modes. The fluid transport and Maxwell's equations are linearized with respect to small perturbations of plasma parameters assumed in the form $\tilde{x} = X(l)\exp(ik_y y - i\omega t)$, where k_y is the wave vector in the direction perpendicular to the unperturbed field lines on magnetic surfaces, ω the frequency and the function X takes into account a smooth variation of the amplitude in the direction l along the field lines arising due to toroidal geometry. The linearization results in the following set of relations:

$$-i\omega\widetilde{n} + \nabla_{\perp}\cdot\left(n\widetilde{\mathbf{V}}_{i\perp}\right) + \widetilde{n}\frac{\partial V_{\parallel}}{\partial l} = 0 \tag{1}$$

$$-i\omega m_i n\widetilde{\mathbf{V}}_{i\perp} + 2T\nabla_{\perp}\widetilde{n} = \frac{1}{c}\left[\widetilde{\mathbf{j}}_{\perp}\times\mathbf{B}\right] \tag{2}$$

$$\nabla\cdot\widetilde{\mathbf{j}} = \nabla_{\perp}\cdot\widetilde{\mathbf{j}}_{\perp} + \frac{\partial\widetilde{j}_{\parallel}}{\partial l} = 0 \tag{3}$$

$$-i\omega m_e n\widetilde{V}_{e,\parallel} = -en\widetilde{E}_{\parallel} - T\frac{\partial\widetilde{n}}{\partial l} - \frac{d(nT_e)}{dr}\frac{\widetilde{B}_r}{B} + m_e\nu_e\frac{\widetilde{j}_{\parallel}}{e} \tag{4}$$

$$\widetilde{E}_{\parallel} = i\frac{4\pi\omega}{k_y^2c^2}\widetilde{j}_{\parallel} - \frac{\partial\widetilde{\phi}}{\partial l}, \qquad \widetilde{B}_r = i\frac{4\pi}{k_yc}\widetilde{j}_{\parallel} \tag{5}$$

where $\widetilde{n}, \widetilde{V}_{i\perp}, \widetilde{V}_{e\parallel}, \overrightarrow{\widetilde{j}}, \tilde{\phi}, \tilde{E}_{\parallel}$ and $\tilde{B}_r$ are the perturbations of the particle density, perpendicular ion and parallel electron velocities, current density, electrostatic potential, parallel electric and radial magnetic fields, respectively; e is the elementary charge, c the speed of light, m_e the electron mass, ν_e the collision frequency of electrons with ions; $V_{\parallel}$ is the plasma velocity along stochastic field lines computed according to Ref. [6]. Eqs. (1)-(5) are combined in a dispersion relation between k_y and ω [7] and the mode with the highest growth rate $\gamma = Im(\omega)$ is selected. The actual level of γ is then adjusted by taking into account the effect of the radial electric field shear [8]. Finally, the contributions of drift modes to the transport coefficients are determined according to the improved mixing length approximation [9].

Transport code RITM

The transport model described above has been incorporated into the 1.5D transport code RITM providing the computation of the radial profiles of different plasma parameters[10]. The densities and fluxes of the main and impurity neutral particles, which enter the plasma volume through the separatrix, are computed by solving kinetic equations in a diffusion approximation. The densities of electrons and impurity ions are determined from corresponding continuity equations by taking into account the particle sources due to ionization of neutrals. The radial distribution of the particle source due to neutral beam injection is taken from the experimental data. Presently the RITM code allows to consider all charged states of He, C, O, Ne, Si and Ar impurities. The density of the main ions is found from the quasi-neutrality condition. The electron and main ion temperatures are determined from the heat transport equations which include convective and conductive transport losses, neutral and impurity radiation, ohmic and additionaly heating by neutral beams and radio waves. The transport coefficients in RITM are determined by taking into account both the neoclassical and anomalous contributions. Additionally to the edge transport considered above the latter includes specific core ion temperature gradient and trapped electron microinstabilities. Several mechanisms for the suppression of these instabilities, e.g., by the radial electric field shear, density gradient, diamagnetic flows, are taken into account. This permits to simulate both L- and H-mode conditions by the RITM code[11].

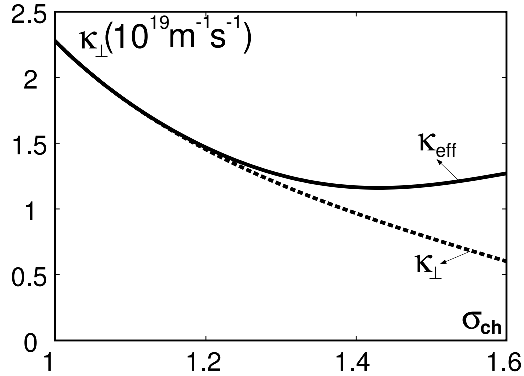

Figure 1: Perpendicular and effective heat conductivities computed with the present transport model for $\rho = 0.87$ in Tore Supra with ED [2].

Results

Figure 1 shows the variation of the perpendicular and effective heat conductivities, $\kappa_\perp$ and κ_{eff}, computed for the Tore Supra plasma parameters [2] at the position $\rho = 0.87$ where a pronounced increase of the temperature gradient has been found with ED. One can see that the effective heat conductivity is reduced by a factor of 2 at a $\sigma_{ch} \approx 1.5$ corresponding to the experimental conditions. This reduction is caused by the decrease in $\kappa_\perp$ occurring due to several reasons. First, through the temperature decrease caused by the plasma cooling in the outer region with strong stochastization, the gyro-Bohm coefficient, generally characterizing anomalous losses, drops. Second, the increase of the temperature gradient activates important channels for turbulence suppression, diamagnetic flows on magnetic surfaces and shear of the radial electric field.

Figure 2 demonstrates the effect of the Dynamic Ergodic Divertor (DED) [4] on the H-mode like plasmas in TEXTOR. The solid curves display the results obtained without effects from the

DED magnetic field perturbation and the broken ones - from calculations with stochastization characterized by a σ_{ch} being by 2 times larger than that found in field line mapping.

Without DED a pronounced edge transport barrier develops with α exceeding α_{cr} near the separatrix. This can cause ELM activity. The barrier is destroyed and a transition to the L-mode conditions occurs when DED is activated. These results are in line with observations on TEXTOR where the switch on of the DED led to the suppression of the strong H_α spikes observed during the H-mode like phase. Simultaneously the time averaged H_α signal was growing up to its level in the L-mode.

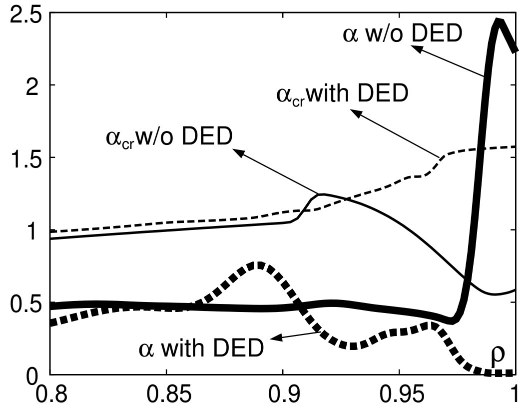

Figure 2: α and α_{cr} for TEXTOR L- and H-modes

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