*29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, P-1.052 (2002)*

Transport Analysis of H-mode Plasmas in Ohmic ALCATOR C-MOD Discharges Based on Neoclassical Theory.

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Abstract

Using experimental temperature and radiation profiles [2], a constant $\eta = \frac{dln(n)}{dln(T)}$ and a power deposition profile based on Spitzer resistivity, the equations for $v_{||}$, v_Θ, and $T_e \approx T_i$, standing for the ambipolarity constraint, the parallel momentum balance, and heat conduction, are solved numerically. It is shown that the total heat diffusivity drops below the neoclassical level but does not reach the subneoclassical level. i. e. the electron heat diffusivity is strongly reduced but finite.

1 Introduction

The revisited neoclassical theory [1] which allows within the framework of a rigorous analytical approach to calculate the two dimensional velocity field on the flux surfaces and the perpendicular ambipolar electric field. The theory is valid in collision dominated plasmas with steep gradients and was able to reproduce the toroidal spin up in ALCATOR [1]
The importance of the theory is underlined by the fact that an interaction between a poloidal or toroidal spin-up and the turbulence driving anomalous transport is believed to be a likely reason for the aforementioned L-H mode transition in tokamaks.
It is also worthwhile to mention that ignition of the International Tokamak Experimental Reactor (ITER) requires an improved confinement regime.

2 Plasma rotation and heat conduction

The main result of the revisited neoclassical theory [1] is an equation describing the radial transport of toroidal momentum in a collisional subsonic plasma with steep gradients:

$$\frac{1}{\eta_2}\frac{\partial}{\partial x}[\eta_2(\frac{\partial g}{\partial x} - \frac{0.107q^2}{1+\frac{Q^2}{S^2}}\frac{\partial ln\ T}{\partial x}\frac{B_\phi}{B_\theta}h)] = T_{CX} \qquad (1)$$

Here $T_{CX} = t_{ci}\frac{\hat{n}}{\hat{\eta}_2}\nu_{cx}g$ accounts for the friction caused by the neutral gas. The characteristic time t_{ci} at the inflection point P_{inf} (Fig. 1) is given by $t_{ci}^{-1} = \frac{1}{m_j n_i L_\psi^2}\eta_{2i}$. m_j

is the ion mass, n_i the ion density at the inflection point, $L_\psi = |(\frac{\partial ln\, T}{\partial r})_i^{-1}|$ the scale length of the ion temperature T at the inflection point, $x = \frac{r - r_i}{L_\psi}$ the radial coordinate, r_i the radius of, P_{inf}, and η_2 the viscosity coefficient [1]. g and h are the normalized and poloidally averaged toroidal and poloidal velocities, $g = \int \frac{d\theta}{2\pi} \frac{u_\phi(\theta)}{v_T}$ $h = \int \frac{d\theta}{2\pi} \frac{u_\theta(\theta)}{v_T}$, respectively. v_T is the constant positive velocity $v_T = \frac{1}{eB_\phi} \frac{T_i}{L_\psi}$ [e is the elementary charge, $T_i = T(r_i)$]. B_ϕ is the toroidal field and B_θ the poloidal field. The velocities Q and S are defined by [1] $\frac{Q}{4v_T} = h - \hat{T} \frac{\partial ln(n^2 T)}{\partial x} \frac{2.5}{4}$ and $\frac{S}{v_T} = \frac{8}{\Lambda'} \frac{B_\phi}{B}$ with $\Lambda' = \Lambda \frac{L_T}{L_\psi}$. The crucial parameter Λ can be written as $\Lambda = \frac{\nu_j}{\Omega_j} \frac{q^2 R^2}{L_T r}$. L_T is the radially dependent decay length $L_T = (\frac{\partial ln\, T}{\partial r})^{-1}$, ν_j the ion - ion collision frequency, Ω_j the ion Larmor frequency, q the safety factor, R the major radius.

Combining the ambipolarity condition with the parallel momentum equation [1] we get in the case of large aspect ratio and circular cross - section a nonlinear relation between the poloidal and toroidal plasma velocities [1].

Because of the large density in ALCATOR (n> 2 $10^{14} cm^{-3}$ at the center) strong equilibration can be assumed and thus the electron temperature equals almost the ion temperature i. e. $T_i \approx T_e \approx T$. We get by adding the electron and ion temperature equation, assuming stationarity and neglecting convection

$$-\frac{1}{r}\frac{\partial}{\partial r} r[-(R_n \chi_e + \chi_i) n_i \frac{\partial T}{\partial r}] + P_{OH} + P_{rad} = 0$$

P_{OH}, P_{rad} are the power source due to ohmic heating and radiation, χ_e, χ_i the electron and ion heat diffusivities and $R_n = \frac{n_e}{n_i}$ is the ratio of the electron density to the ion density. The total heat diffusivity is given by $\chi = R_n \chi_e + \chi_i$. The subneoclassical ion heat diffusivity is $\chi_{sub} = [1 + 1.6 \frac{q^2}{1 + \frac{Q^2}{S^2}}] n_i \nu_i r_{ci}^2$ which equals the neoclassical ion heat diffusivity $\chi_{neo} = [1 + 1.6 q^2] n_i \nu_i r_{ci}^2$ for $\frac{Q}{S} = 0$ (Λ=0)

3 Solution method, results and discussion

Equation (1) is a second order equation for g, the normalized toroidal velocity. This equation is replaced by two first order equations.

In addition we have the equation for the poloidal rotation. For a given temperature and density and normalized toroidal velocity g this equation is solved for h by means of a solver for transcendental equations. We assume a symmetric streaming of the scrape-off plasma into the divertor. This yields as boundary value h$(r = r_s) = 0$. We assume moreover $g(r = r_s) = 0$ because of the absence of momentum sources such as neutral beam injection (NBI) and because neutrals may be reducing $g(r = r_s)$ to a low value. $\Lambda^2(r_s) = \Lambda_s^2$ is for given set of device parameters determined by the equation for h. [1].

Two ODE's are added to account for the heat conduction. The first is the equation for the total heat flux density $\frac{1}{r}\frac{\partial}{\partial r} rQ + P_{OH} + P_{rad} = 0$ with $Q = -(R_n \chi_e + \chi_i) n_i \frac{\partial T}{\partial r}$. The second is the temperature equation $-(\chi_e R_n + \chi_i) n_i \frac{\partial T}{\partial r} = Q$.

The input data are those of ALCATOR C-MOD [2] with T_i=165 eV, $n_i = 1.87\ 10^{20} m^{-3}$, $L_\psi = 0.76$ cm, r_i=20.8 cm, $r_s = 21.5$ cm, $\epsilon = 1.6$, Z_{eff_i}=1.57, Z=0.875, η= 1.6, R = 67 cm, $B_\theta = 0.625$ T and $B_\phi = 5.2$ T. Here Z_{eff_i} and Z are defined by $Z_{eff}(r) = Z_{eff_i} \hat{T}^Z$, i. e. Z_{eff_i} is $Z_{eff}(r)$ at the inflection point. The experimental temperature with the pedestal in the edge profile can be seen in Fig. 1. In contrast to the calculations in [1] the total plasma cross-section is accounted for. However, since the theory in [1] is valid in the edge only, the velocities shown here for the central core may be not relevant. The radiation profile (Fig. 2) [3] is strongly peaked at the plasma edge, entailing a reduction in the total deposited power $P(r) = (2\pi)^2 R_0 \int_0^r (P_{OH} + P_{rad}) r dr$. Fig. 3 shows the toroidal rotation speed which jumps due to the temperature pedestal to around 30 $\frac{km}{sec}$ [1]. The total heat diffusivity had to be adjusted to reproduce the measured profile. Three approaches were used:

1. A parabolic dependence (χ_{tot_1}) is used in $0 < r < r_i - \Delta$ and subneoclassical behaviour in the pedestal (with a width 2Δ of a few millimetres and the centerpoint at r_i=22.5 cm)
2. In $0 < r < r_i - \Delta$ the coefficient obtained by inverting the temperature profile is used and inside the pedestal $r_i - \Delta < r < r_i + \Delta$ the subneoclassical dependance is used (χ_{tot_2}).
3. The coefficient obtained by inverting the temperature profile is used everywhere.

The temperature dependence in the case (1) is inaccurate in approaching the pedestal (Fig. 4). This inproves considerably in using the approach (2) (Fig 5). Using the diffusivity obtained by inversion and computing the temperature profile (as a check) we obtain the experimental profile. The total heat diffusivity χ_{tot} may be compared with neoclassical and subneoclassical one (Fig. 6). Assuming that the ion heat diffusivity is caused by binary (ion - ion) collision only, the difference between the total and the (sub)neoclassical one is the electron heat diffusivity (if $R_n \approx 1$). χ_{tot} is normally much larger than the ion heat diffusivity. However, in the vicinity of of the inflection point χ_{tot} lies in between the neoclassical and the subneoclassical diffusivity (it is roughly the mean value of both). This clearly shows that in this region $\chi_{tot} < \chi_{neo}$ holds. The electron transport is small but finite. If one assumes that (at the inflection point) the ion heat diffusivity is subneoclassical, then the electron heat diffusivity is $\chi_e \approx 0.1 \frac{m^2}{sec}$, i. e. of the same order as χ_{sub}.

References

[1] A. Nicolai, A. L. Rogister, U. Daybelge, Procedings of the 8th PET - conference, to be published

[2] J. E. Rice, J. A. Goetz, R. S. Granetz, M. J. Greenwald, A. E. Hubbard et al., Phys. Plasmas 7 (2000) 1825

[3] R. Boivin, private communication

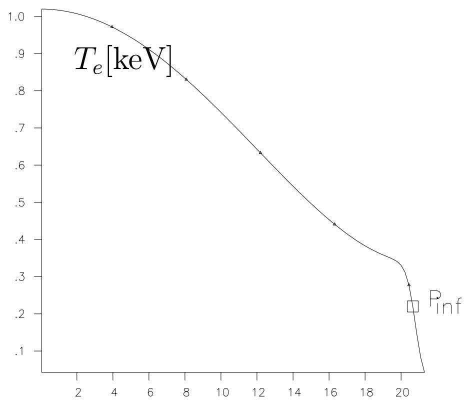

Fig. 1

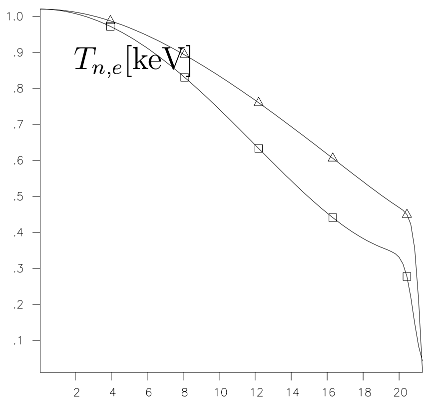

Fig. 4

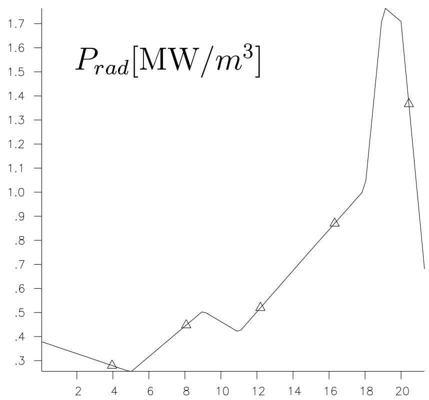

Fig. 2

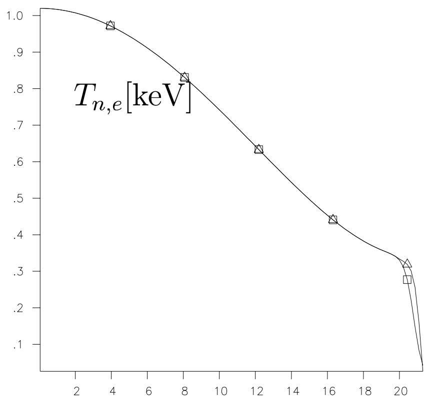

Fig. 5

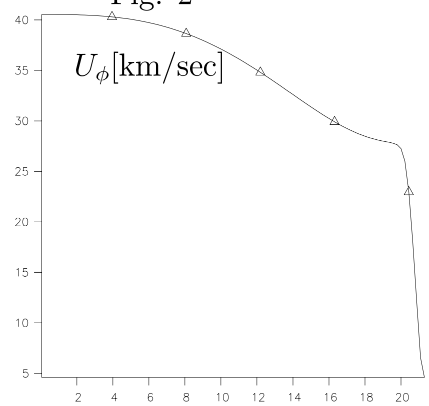

Fig. 3

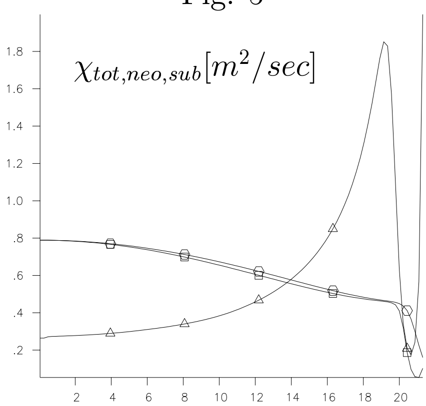

Fig. 6

Temperature and radiation profile in ALCATOR C-MOD (Figs. 1, 2),
Toroidal velocity U_ϕ (Fig. 3), Temperature profiles for χ_{tot_1} and χ_{tot_2} (Figs. 4, 5)
Fig. 6: Temperature diffusivities χ_{tot} (triangles),χ_{sub} (quadrangles),χ_{neo} (hexagons)