33rd EPS Conference on Plasma Phys. Rome, 19 - 23 June 2006 ECA Vol.**30I**, P-4.148 (2006)

Paleoclassical Electron Transport Barriers in RTP

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1. Introduction This paper reports on a test of the paleoclassical transport model [1] on experimental results of the former Dutch RTP tokamak. In the following we first briefly recall the RTP experiments and the main features of the paleoclassical model. Then simulations of two kinds of RTP experiments with the paleoclassical model are presented. The paleoclassical model is observed to reproduce both cases quite well, both qualitatively and quantitatively. The similarities and differences between experiments and paleoclassical simulations, in terms of evolution of T_e and q profiles, will be discussed.

2. Electron thermal transport barriers in RTP On the former Dutch RTP tokamak (major/minor radii $R_0 = 0.72/a = 0.164$ m; plasma current $I_p \leq 150$ kA; magnetic field $B_T \leq 2.4$ T, pulse duration ≤ 600 ms) it was found that electron thermal transport has a layered structure: zones with high diffusion coefficient (χ_e) alternate with narrow zones of low χ_e, i.e. electron Internal Transport Barriers (eITBs). For the EC heating in the experiments reported here a 110 GHz, 350 kW, 200 ms gyrotron was used, launching from the low field side in 2nd harmonic X-mode. Mirrors focus the power to a spot with full width half maximum of $\simeq 0.1 \cdot a$. In the following, the paleoclassical model is tested on two sets of RTP results, described in detail in [2,3,4].

First, in series of similar discharges the normalized power deposition radius ($\rho_{dep} \equiv r_{dep}/a$) was scanned in steps of $\leq 1\%$ by small changes of B_T. For one representative dataset Fig.1 shows steady state $T_e(0)$, measured by Thomson scattering, as function of ρ_{dep}. Strikingly, $T_e(0)$ does not adapt gradually to the changing ρ_{dep}; instead, sharp transitions between a finite number of discrete levels are observed. Note that the transitions occur for variations of ρ_{dep} as small as 0.01, significantly smaller than the width of the power deposition. Neoclassical calculations of the q profiles showed [2] that the sharp transitions correspond to the jump of q_min across a low order rational value, i.e. 1, 4/3, 3/2, 2, 5/2, and 3.

Second, during a discharge ρ_{dep} was scanned dynamically from 0.2 to 0.6 by sweeping B_T from 2.09 to 2.27 T in 175 ms. The same levels and transitions were observed as before, see Fig.2; again the transitions were much sharper than could be expected from the width of the power deposition.

These results called for a transport model in which χ_e is a direct function of q, where zones of high thermal conductivity (corresponding to the plateaux in Fig.1) are separated by insulating shells (producing the transitions); the latter are tied to low order rational q values. Indeed such an empirical model, in which the ITBs are prescribed as function of q only, could successfully reproduce both kinds of experiments [2].

3. The Paleoclassical Transport model A new model for an irreducible minimum level of radial electron heat transport, the paleoclassical model, was introduced recently [1]. The key hypothesis is that in resistive, current-carrying toroidal plasmas the electron guiding centers diffuse with small bundles of poloidal magnetic flux on the magnetic ("skin") diffusion time scale.

What limits the parallel equilibration length L of T_e along field lines depends on the collisionality. In a collisional plasma it is simply the electron collision length $\lambda_\mathrm{e} = v_{\mathrm{T}_\mathrm{e}}/\nu_\mathrm{e}$.

For a collisionless plasma we consider the subset of all rational surfaces m/n with $n < n_{\rm max}$ for some $n_{\rm max}$. The distance between two surfaces of this subset is at least $\delta \sim 1/({n_{\rm max}}^2 q')$, with an appropriate modification when $q' = 0$. Putting $\delta = \delta_{\rm e}$, the electromagnetic skin depth, we get

$$n_{\rm max} = (\pi \delta_{\rm e} q')^{-0.5} \tag{1}$$

which defines the subset of field lines which can (just) radially diffuse over their entire length. Then the length is $l_{\rm max} = \pi R_0 q n_{\rm max}$.

However, near a low order magnetic surface $q^0 = m^0/n^0$, the relevant length is $l_{n^0} = \pi R_0 q^0 n^0$ which may be a factor of ~ 5 smaller than $l_{\rm max}$. Then the paleoclassical classical electron heat diffusivity is given by

$$\chi_{\rm e}^{\rm pc} = \frac{3}{2}(M+1)D_\eta \quad \text{with} \quad M = \min(f l_{\rm max}, f\lambda_{\rm e}, l_{n^0})/(\pi R q) \tag{2}$$

where D_η is the magnetic field diffusivity, $D_\eta = \eta/\mu_0$ where η is the resistivity; f is a numerical factor of order 1-2; in this paper $f = 2$.

The paleoclassical model also predicts convective heat transport, usually directed inward, i.e. a heat pinch. Therefore the paleoclassical 'power balance' $\chi_{\rm e}$ will be generally somewhat smaller than $\chi_{\rm e}^{\rm pc}$. For the sake of simplicity we will omit the convective term from our simulations. Paleoclassical transport is expected to be the dominant electron thermal transport mechanism in low $T_{\rm e}$ plasmas (up to ~ 1 keV in RTP).

4. Paleoclassical Transport predictions for RTP The paleoclassical model has been tested in self-consistent predictive simulations, starting from given profiles of $T_{\rm e}$, $T_{\rm i}$ and $n_{\rm e}$. For $T_{\rm e}$ and $n_{\rm e}$ smoothed measured profiles are used. Since there was no regular measurement of the $T_{\rm i}$ profile on RTP, a parabolic profile was used with $T_{\rm i}(0) = 0.4$ keV, corresponding to $\chi_{\rm i}$ a few times $\chi_{\rm i}^{\rm nc}$. $Z_{\rm eff}$ was taken from experiment, i.e. calculated from $I_{\rm p}$ and $V_{\rm loop}$, assuming no radial dependence; typically $Z_{\rm eff} \sim 2$. The simulations calculate the co-evolving $T_{\rm e}$, $\chi_{\rm e}^{\rm pc}$, and q profiles, keeping $n_{\rm e}$ and $T_{\rm i}$ fixed; they are run until a final equilibrium is reached, typically after 50-200 ms. Note that the energy confinement and current diffusion times ($\tau_{\rm E}$, $\tau_{\rm cd}$) in RTP are typically 2-5 and 20-50 ms.

To get a flavour of the way the paleoclassical model works, first a standard ohmic RTP discharge is considered. Fig.3 shows the smoothed measured $T_{\rm e}$ profile for such a discharge, and the corresponding $\chi_{\rm e}^{\rm pc}$, q and j profiles in blue. Strong barriers near $q = 1, 2, 3$ are seen; weaker barriers are visible for $q = m/n$ with $n = 2$ and $n = 3$. Outside $\rho \simeq 0.8$ the plasma is in the collisional paleoclassical regime. The same plot also shows in red the final profiles after 50 ms. In this case the paleoclassical model gives a very good reproduction of the profiles.

The paleoclassical simulations of the shot-to-shot scan are shown in Fig.1. Due to the strong scaling $D_\eta \sim {T_{\rm e}}^{-3/2}$ in the collisionless regime, $\chi_{\rm e}^{\rm pc}$ becomes extremely low in the hot core for small ρ_{dep}. This causes run-away behaviour for simulations with $\rho_{dep} <\sim 0.25$. This was accounted for by imposing an ad-hoc sawtooth crash model, with crashes occurring when $q(0) < 1$ with a frequency of $\simeq 2$ kHz, corresponding to RTP conditions. Results both with and without sawteeth are shown. With imposed sawteeth a quite good reproduction of the experimental data is obtained. However, the transitions between the plateaux in the simulations are at larger radii than in the experiment; the cause of this is discussed below.

The paleoclassical simulations of the dynamic scan are shown in Fig.2, showing good qualitative agreement.

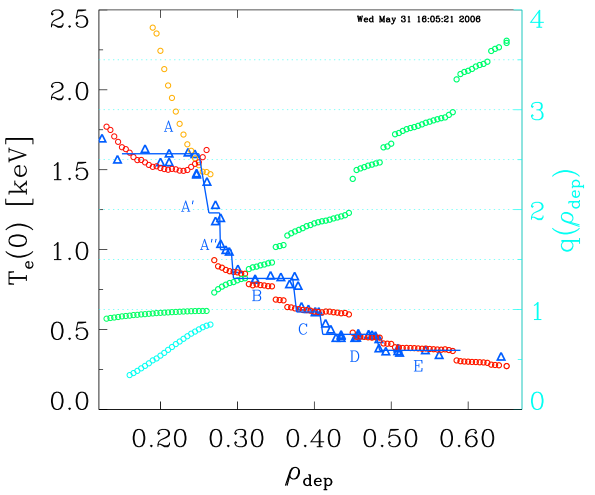

Figure 1: *Simulations with the paleoclassical transport model. Shown are* $T_e(0)$ *from experiment (blue triangles) and from the paleoclassical simulations both with and without imposed sawteeth (red and orange circles, respectively). Moreover, the value of* $q(\rho_{dep})$ *from the simulations is shown (green/blue circles with/without imposed sawteeth), values along right y-axis.*

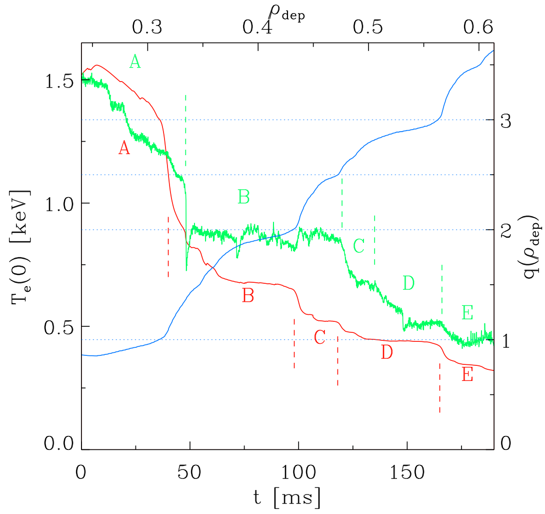

Figure 2: *Simulations with the paleoclassical transport model of the* ρ_{dep} *sweep. Shown are time traces of* $T_e(0)$ *from experiment (green) and from the paleoclassical simulation (red). Moreover, the value of* $q(\rho_{dep})$ *from the simulations is shown (blue), values along right y-axis. the levels A$\cdots$E are indicated, both for experiment and simulation.*

The measured T_e profiles are hollow for levels B$\cdots$E, which is not accounted for by any regular loss mechanism ($e-i$ exchange, radiation). In empirical simulations this was solved for by imposing outward heat convection in the region $\rho < \rho_{dep}$. As there is no such term in the paleoclassical simulations, the T_e profiles produced by the paleoclassical simulations are flat inside ρ_{dep} This also causes difference in q profiles, i.e. the central q is lower in paleoclassical simulations. Consequently, the transitions (loss of a low q rational) take place at larger ρ in the paleoclassical simulations. This is illustrated in Fig.4, which compares T_e q and χ_e profiles for $\rho_{dep} = 0.447$ from the paleoclassical with the empirical simulation; the latter is very close to the experimental T_e profile. Although the paleoclassical simulation reproduces the experimental T_e profile satisfactorily, it misses the hollowness inside ρ_{dep}, and the main eITB just outside ρ_{dep} is the one near $q = 3$ instead of $q = 5/2$.

Finally, the paleoclassical model nicely reproduces the sharp transitions. Fig.5 shows the dramatic difference between $\rho_{dep} = 0.446$ and 0.447.

Acknowledgements. This work, supported by the European Communities under the contract of Association between EURATOM/FOM, was carried out within the framework of the European Fusion Programme with financial support from NWO. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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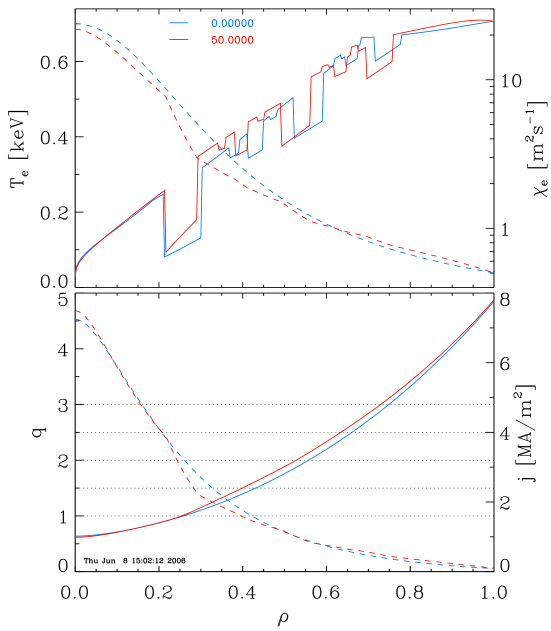

Figure 3: *Paleoclassical simulation of an ohmically heated RTP discharge. In blue the parametrized measured* T_e *profile, the corresponding* χ_e^{pc} *(dashed and full lines, upper panel), and the corresponding q and j profiles (lower panel, full and dashed lines, respectively). The final equilibrium profiles are shown in red.*

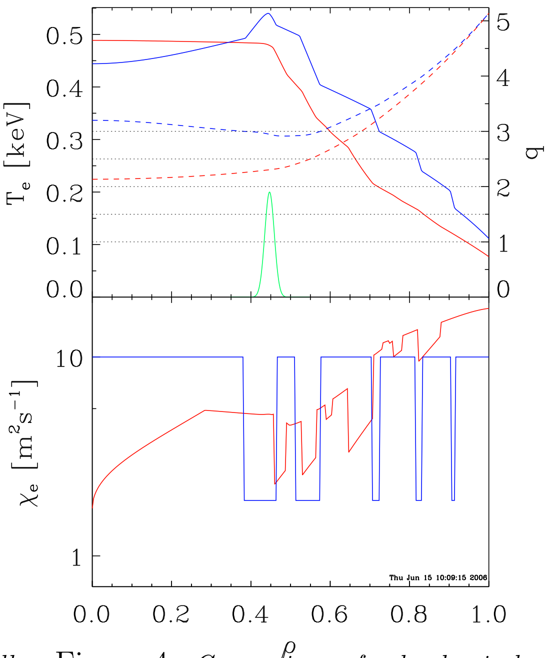

Figure 4: *Comparison of paleoclassical and empirical simulations for* ρ_{dep} *= 0.447 (red and blue, respectively). Shown are* T_e *and q (upper panel, full and dashed lines) and* χ_e *(lower panel). Also is shown the ECRH power deposition profile (green).*

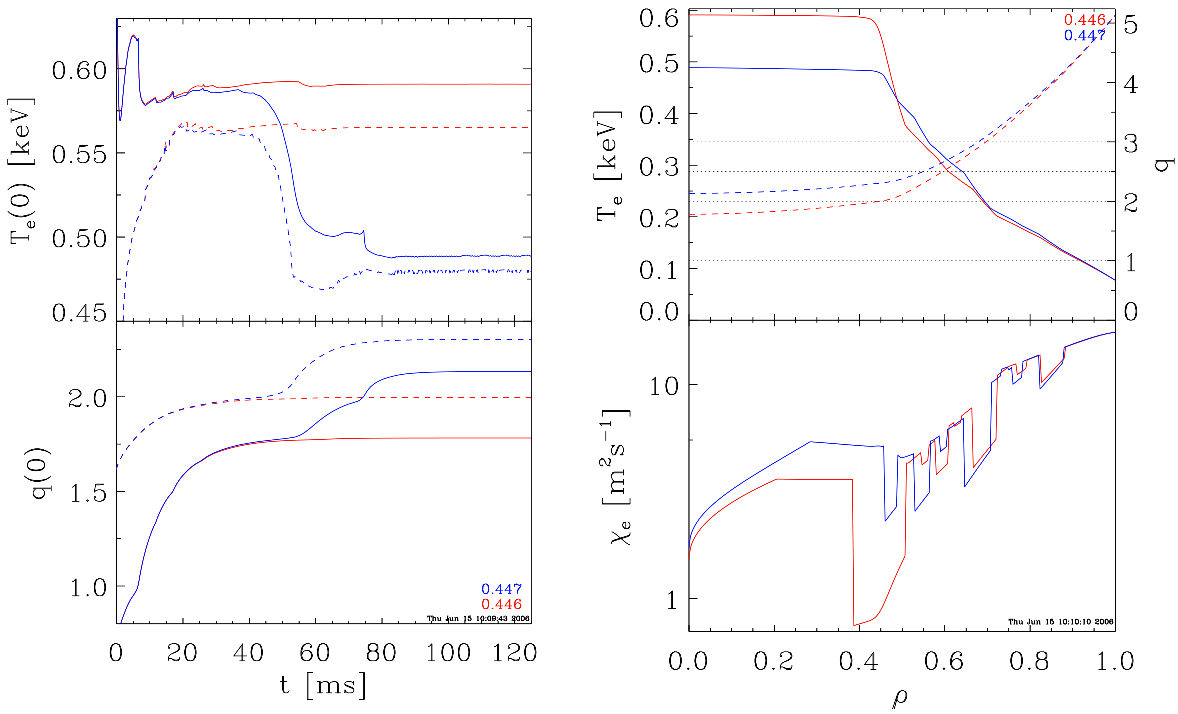

Figure 5: *Paleoclassical simulations comparing* ρ_{dep} *= 0.446 (red) and 0.447 (blue).*