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The Role of Convective Heat Losses in the START Ohmic Plasma Confinement

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1. INTRODUCTION

The START experiments at UKAEA Culham Lab has provided the first results on energy confinement in the Spherical Tokamaks (ST) [1] including access to H-modes in both NBI-heated and Ohmic plasmas. The cold neutrals in the plasma determine the important source of the heat losses. It is especially important for START, where the ratio of the plasma volume V_p to the chamber volume V_c is low (V_p/V_c~0.07) and a large reserve of neutrals exists. We investigate the plasma transport in START to find the effect of neutrals on the confinement. The Ohmic stage of discharges after NBI cut off is chosen for the analysis. The Canonical Profiles Transport Model (CPTM), adapted for low aspect ratio tokamaks, is used to simulate the electron and ion heat transport. The spatial distribution of neutral density taken from the solution of the slab model (by the ASTRA code) provides the information on the particle source due to ionization and the particle flux, q_n, setting the convective heat flux $q_{e,i}^{con} = 5/2 q_n T_{e,i}$. The deviation of the calculated electron temperature from the experimental one is considered as the model quality control.

2. THE MODEL

We present here the basic expressions of the CPTM, which we used in the calculations [2]. The set of transport equations consists of the equations for the electron and ion temperatures and for the poloidal magnetic field. The equilibrium is obtained by the solution of the Grad-Shafranov equation. We use the canonical profiles of the ion and electron temperatures and pressures in Kadomtsev's form

$$T_{kc}(\rho)/T_{kc}(0)=(1+\rho^2/a_j^2)^{-1}, \qquad p_{kc}(\rho)\,/\,p_{kc}(0)=(1+\rho^2/a_j^2)^{-3/2} \tag{1}$$

where k = e, i; ρ is the radial coordinate ($0<\rho<a$), $a_j=a(q_0/(q_s-q_0))^{1/2}$ is the current radius, q_0 is the safety factor on the magnetic axis, q_s is the safety factor on the magnetic surface which surrounds the current I_s, equal to a fixed fraction of the total plasma current $I_s=sI_p$ ($0.9<s<0.95$). We put also $T_{ec}(\rho)=T_{ic}(\rho)=T_c(\rho)$ and assume the following form of the heat fluxes:

$$q_k=q_k^{con}+q_k^{an}+q_k^{PC} \qquad (k = i, e) \tag{2}$$

where

$$q_k^{an} = -\kappa_k^{an}\frac{\partial T_k}{\partial \rho}, \quad \kappa_k^{an}=n\chi_k^{an} \qquad q_k^{PC} = -n\chi_k^{PC}\,(\partial T_k/\partial\rho - (T_{kc}'/T_{kc})\,T_k)\,F_k(z_{pk}) \tag{3}$$

$$F_k(z_{pk})=\exp(-z_{pk}^2/2z_{0k}^2) \qquad z_{pk} = a^2/\rho\;\partial/\partial\rho\;\ln(p_k/p_{kc}), \tag{4}$$

We choose the following transport coefficients:

$$\kappa_k^{PC}=\alpha_k^{PC}\,(1/M)(a/R)^{0.75}\,q(a/2)q_{cyl}(a)(T_k(a/4))^{0.5}\,\overline{n}\,(3/R)^{1/4}/B_t=\text{const}(\rho) \tag{5}$$

$$\chi_e^{an}=\text{const}(\rho)=\tilde{\alpha}_e\frac{(T_e(a/2))^{1/2}}{n(a/2)R}f_e^{an}(q,\beta,\nu^*,a/R) \quad (6)$$

$$f_e^{an}(q,\beta,\nu^*,a/R)=9.4\,(4/q_s)\,(a/R)^{2.5}\,,\quad \chi_i^{an}=\chi_e^{neo}\,,\quad q_{cyl}=\frac{5a^2B_t}{I_pR}\frac{1+k^2}{2} \quad (7)$$

$$\alpha_e^{PC}=3.5,\quad \alpha_i^{PC}=5,\quad \alpha_e\approx 2,\qquad z_{0k}=7-8 \quad (8)$$

Here M is the relative mass of the main plasma ions, k is the elongation. We use the following units: T in keV, B_t in Teslas, a and R in m, n in 10^{19} m^{-3}, χ_k in m^{2}s^{-1}, κ_k in 10^{19} m^{-1}s^{-1}. The full neoclassical conductivity, σ, is used throughout.

3. THE ROLE OF NEUTRALS AT LOW DENSITY SHOTS

We analyse the Ohmic stage (after NBI cut off) of the set of 12 shots (##36065–36090), with similar currents (I_p=0.185–0.23 MA), but different plasma densities ($\bar{n}$=0.81–6.72×10^{19} m^3). The ELMs are observed in these shots so they are suspected to the H-mode. The calculation results are compared with the experiment by the linear-averaged deviation:

$$dT_1=\sum\left(T_e^{exp}-T_e\right)\Big/\sum T_e^{exp} \quad (9)$$

where T_e^{exp} are measured by the 30-point TS diagnostic. At first we consider the plasma transport for the L-mode version of the CPTM ($F_k(z_{pk})\equiv 1$), without cold neutrals. **Figure 1** shows the deviation dT_1 versus chord-averaged density for chosen set. This figure shows that our calculations overestimate the electron temperature for low density shots and underestimate it for high density shots. To improve our description of low density shots we add the convective heat losses. The high density shots will be described by suggesting the H-mode improvement of the confinement.

To include the convective heat flux in the energy transport equations one has to know the radial particle flux in the plasma q_n. It can be determined by the particle source S using the continuity equation:

$$\text{div}\,q_n=S-\partial n/\partial t\,,\quad S=<\sigma^{ion}v_e>n\cdot n_n\,, \quad (10)$$

where n=$n(t)$ and $\partial n/\partial t$ are taken from the experiment, σ^{ion} is the cross section of the ionisation by electrons, n_n is the neutral density. We take the edge neutral density n_n^a in the range 0-2×10^{17} m^{-3}, and their energy 4 eV, that is in the agreement with the estimations [3].

The convective energy losses are significant in the low density plasma because it is transparent for neutrals. **Figure 2** shows the electron temperature profiles, calculated for the different neutral densities in the low density shot #36066 ($\bar{n}$=0.95×10^{19} m^{-3}), and the experimental points (squares). The value of $dT_1\approx 0$ is obtained at $n_n^a\approx$1.5×10^{17}m^{-3}. **Figure 3** shows that for the low density shots (##36066,68) dT_1 rapidly rises with the neutral density n_n^a increase, but dT_1 is hardly changed for medium and high density shots (##36085,87).

4. THE INFLUENCE OF NEUTRALS ON POSSIBLE L-H TRANSITION

Here we consider the shots with medium and high plasma densities (n>3) when cold neutrals do not penetrate deeply. Let us estimate the threshold power of L – H transition taking into account the convective losses. The analytic criterion for the L-H transition in the CPTM has the form [2]

$$F_k<<1\quad\text{or}\quad |z_{pk}|<z_{0k} \quad (11)$$

The criterion (11) can be transformed to the constraint on the total deposited power

$$P_{tot} - P^{con} > P_{thr}\,, \qquad (12)$$

where P_{thr} (MW)=0.13 (9-$a/L_n(a)$)R $T_e(a)$ κ, $P^{con}=(q_e^{con}(a)+q_i^{con}(a))S_p$ is the total convective heat flux at the plasma edge, S_p is the plasma surface area, $\kappa=n\chi=a^2n/\tau_E$ is the heat conductivity, τ_E is the energy confinement time, $L_n = n/n'$ is the characteristic density length just before the L-H transition. For START parameters a=0.25 m, R=0.32 m, T_e(a)=0.03 keV, $\bar{n}=6\times10^{19}$ m^{-3}, τ_E=0.003 s, we find P_{thr} (MW)=0.16 (9-$a/L_n(a)$). The measurements of density profiles on START show that the edge density gradient for the shots about to undergo an L-H transition is large: $a/L_n(a)$~6-8. So we obtain the estimate P_{thr}~0.16-0.48 MW, which is significantly larger than the values obtained from usual scalings and is comparable to Ohmic heating power. The criterion (12) differs from the traditional ones by the term P^{con} at the left hand side. So the convective losses can impede the L-H transition and diminish the pedestal temperature in H-mode. It is one of the reasons, why the pedestal may not be visible in the experiment in spite of the existence of ELMs, which confirm the transition to the H-mode.

The influence of neutrals is illustrated by **figure 4**, where the electron temperature profiles T_e(r) for the medium density shot #36085 calculated by the full version of the CPTM for different neutral densities at the edge are compared with the experimental points T_e^{exp}. The pedestal of electron temperature changes from T_e^{ped}~150 eV for $n_n^a=0$ down to T_e^{ped}~40 eV for $n_n^a=0.6\times10^{17}$ m^{-3}.

In **figure 5** the dependence of the deviation dT_1 on the edge neutral density n_n^a is shown both for L- and H-mode versions of the CPTM for two shots with medium and high densities ($\bar{n}=3.9$ for #36085, $\bar{n}=5.75$ for #36087). It is seen that neutrals strongly influence the H-mode even at very high density. The intersection of the H- branches with the line $dT_1=0$ provides the best correspondence between the modelling and the experiment, and can be used for the estimates of the neutral density. Figure 5 shows that this intersection is occurs at the density $n_n^a=0.3–0.4\times10^{17}$m^{-3} Using the procedure of the minimization of $|dT_1|$, it is possible to find the correspondent values of the neutral density for other shots. **Figure 6** shows the calculated values of n_n^a for the chosen set of shots versus plasma density. It is seen that the neutral density is very high at low plasma density.

5. CONCLUSIONS

Convective heat losses generated by the cold neutrals can noticeably degrade the energy confinement in START. Convection was found to have a strong effect in the low density shots ($\bar{n}<2\times10^{19}$ m^{-3}) where the convection transports more than a half of the energy flux. In the high density plasma ($\bar{n}>3.5\times10^{19}$m^{-3}) the neutrals do not penetrate deeply but the another effect, the strongly influence the H-mode, is possible. Convective losses impede the possible L-H transition and can diminish the external thermal barrier. The mechanism of convection is universal as it is determined by the neutral density only and does not depend on the value of the heat diffusivity. The modeling by the CPTM shows that the H-mode in START can be achieved, but an improvement of confinement could be low due to high convective heat losses near by the edge. To obtain an H-mode discharge with high energy confinement, it is necessary to diminish the neutral density down to $n_n^a=(0.1–0.2)\times10^{17}$m^{-3}.

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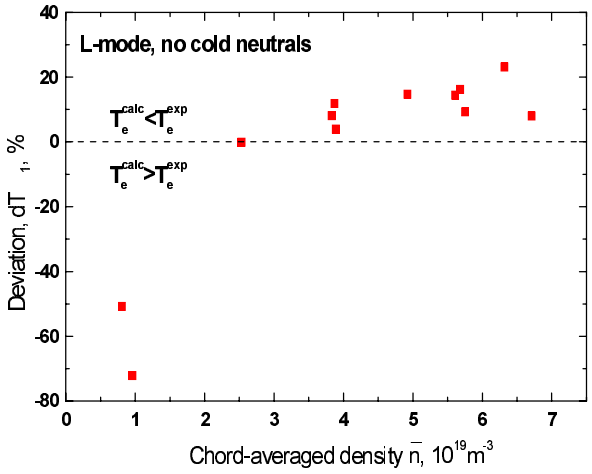

Fig.1

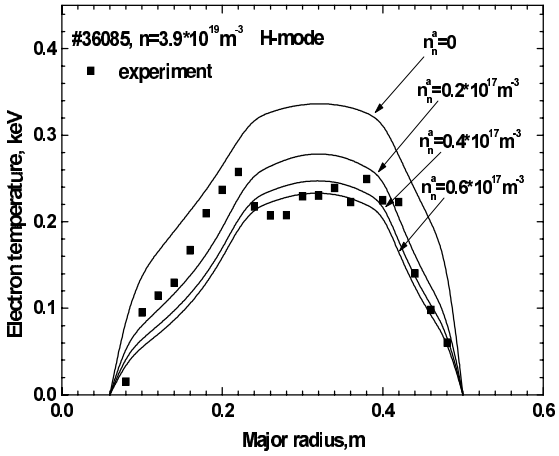

Fig.4

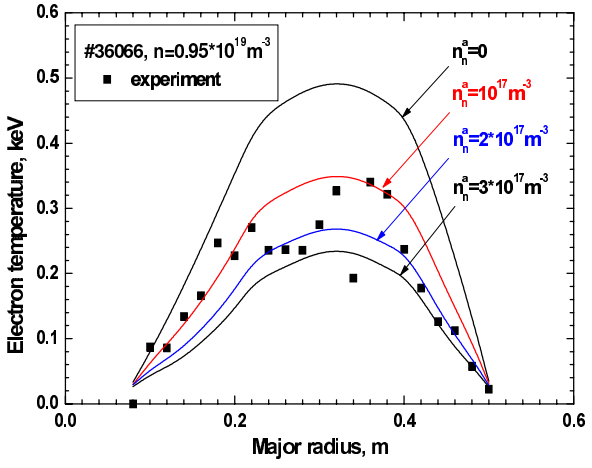

Fig.2

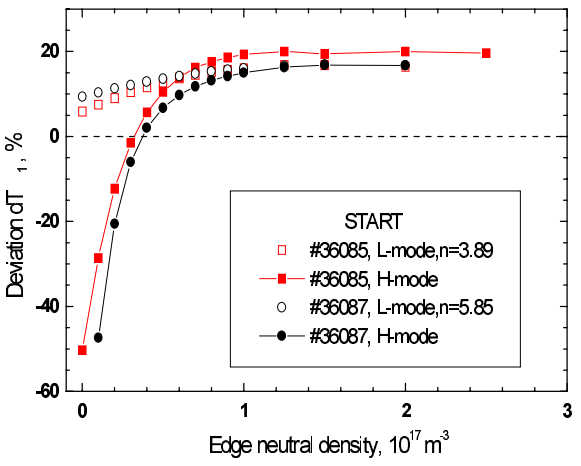

Fig.5

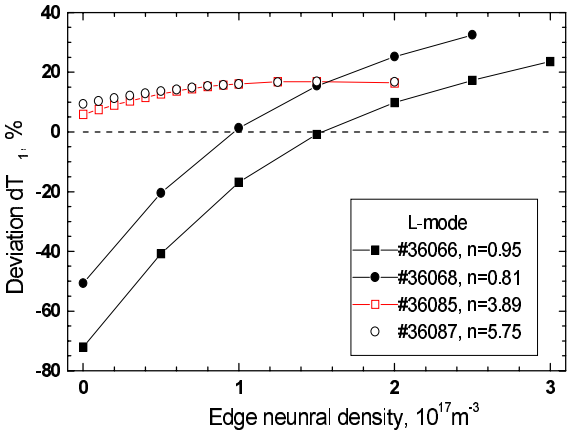

Fig.3

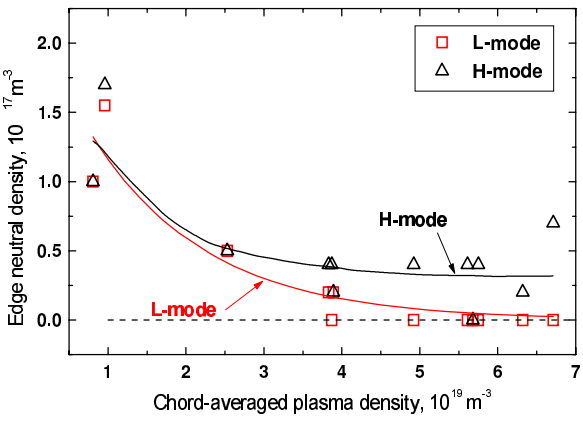

Fig.6