Simulation of the Energy and Particle Transport in START and T-10 Tokamaks

A.Yu. Dnestrovskij, Yu.N. Dnestrovskij, M.P. Gryaznevich[1], Yu.V. Esipchuk, V.V. Chistyakov, N.A. Kirneva, S.E. Lysenko, A. Sykes[1], K.N. Tarasyan, M.J. Walsh[2]

Russian Research Centre 'Kurchatov Institute', Institute of Nuclear Fusion, Moscow, Russia
[1]Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon, UK
[2]Walsh Scientific Ltd., Abingdon, Oxon, OX14 3DB, UK

1. Introduction

The role of the neutral component in START during the L-H transition was considered in our previous work [1]. We found that the neutrals impede the appearance of the H-mode by the increase of the convective losses for low density plasma ($\bar{n} < 2\times10^{19}\,\mathrm{m^{-3}}$) and for high density plasma ($\bar{n} > 6\times10^{19}\,\mathrm{m^{-3}}$) by the partial destruction of the electron temperature pedestal that is the characteristic feature of ELMy H-modes on START [2]. In this Report we apply these ideas to the analysis of shots from the START and T-10 tokamaks by using the full Canonical Profiles Transport Model (CPTM) including the density diffusion equation.

In START the convective heat flux is a significant part of the total heat flux. So if we know (by modelling) the heat conduction term then the convective flux and, as a consequence, the particle flux can be found from the energy balance only. On the contrary, in T-10 the convective term does not give a significant contribution to the heat flux in the plasma core due to the much lower value of cold neutral density. In this case for the of a particle balance analysis we have to use the particle diffusion equation. Nevertheless the neutrals can play a noticeable role near by the edge. Experimentally values of the temperature pedestals are very unclear both in START and T-10, but the density has a very steep gradient at the edge confirming the existence of the transport barrier. H-modes in START and T-10 are very similar in spite of the large difference in several plasma parameters: the cold neutral density in START is an order of magnitude higher than in T-10 but the energy confinement time is an order of magnitude less. The width of the transport barrier and the density gradient are approximately the same, but the transport coefficients near the edge are very different.

The ITER scaling for the threshold power of the L-H transition depends on the *global* plasma parameters. In contrast, the similar CPTM scaling includes also the plasma *local* edge parameters. The application of the latter scaling to both START and T-10 shows the reasonable coincidence with experiment. Note that the ITER scaling gives for START the extremely low value of the threshold power, which apparently contradicts to experiment.

2. Model description

We use the set of transport equations for the electron and ion temperatures, plasma density and poloidal magnetic field. The heat and particle fluxes are as follows [3]:

$$Q_k = 3/2\, Q_n T_k + Q_k^{an} + Q_k^{PC} \quad (k = i, e),\quad Q_n = Q_n^{an} + Q_n^{PC} \tag{1}$$

where

$$Q_k^{an} = -\,\kappa_k^{an}\,\partial T_k/\partial\rho,\quad \kappa_k^{an} = n\chi_k^{an},\qquad Q_n^{an} = -D^{an}\,\partial n/\partial\rho \tag{2}$$

$$Q_k^{PC} = -n\chi_k^{PC}\,(\partial T_k/\partial\rho - (T_c'/T_c)\,T_k)\,F_k(z_{pk}) \tag{3}$$

$$Q_n^{PC} = -D^{PC}\,(\partial n/\partial\rho - (n_c'/n_c)\,n)\,F_e(z_{pe}) \tag{4}$$

$$F_k(z_{pk}) = \exp(-z_{pk}^2/2z_{0k}^2),\qquad z_{pk} = (a^2/\rho)\,\partial/\partial\rho\,\ln(p_k/p_c), \tag{5}$$

$F_k(z_{pk})$ is a forgetting factor defining the transition to the H-mode. T_c, n_c and p_c are canonical profiles [4]. The fluxes (3-4) that are proportional to the difference between relative gradients of real and canonical profiles describe the plasma "Profile Consistency".
The transport coefficients are the same as in [3] with a supplement for the diffusion equation

$$D^{an} = D_0, \qquad D^{PC} = C\,\chi_e^{PC}, \tag{6}$$

Here D_0 and C are the model coefficients, which have to be defined from the experiment. The particle source S_n is defined by the flux of wall neutrals and gas puff.

3. Conditions for the L-H transition

The conventional ITER scalings for the threshold power implicitly assume that the temperature gradient at the edge defines the boundary of the L-H transition. We assume in the CPTM that the threshold of the transition is defined by the pressure gradient. This physically corresponds to the force balance equation $dp_i/dr = enE_r + (en/c)(v_{i\theta}B_\varphi - v_{i\varphi}B_\theta)$, and to the usual approach of the modern models, where the electric field plays a key role.
The criterion for the L-H transition is as follows:
$P_{tot} - P^{con} - P^{rad} > P_{thr,}$ where the threshold power P_{thr} in the CPTM has the form [5]:

$$P_{thr}\ (\mathrm{MW}) = 0.13\ (z_0 + z_q - z_n)R\,T_e(a)\,\kappa \tag{7}$$

Here P^{rad} is the radiated power, $\kappa = n\chi = a^2 n/(2\tau_E)$, $z_q = 3\,(1-1/q_a) \approx 2 - 2.5$, $z_n = -an_a'/n_a$ is the dimensionless density gradient at the edge in the L-mode before the L-H transition, $z_0 = 9$. For typical START parameters: a = 0.25 m, R = 0.3 m, $T_e(a)$ = 0.03 keV, $\bar{n} = 4\times10^{19}$ m^{-3}, τ_E = 0.002 s and T-10 parameters a = 0.3 m, R = 1.5 m, $T_e(a)$ = 0.1 keV, $\bar{n} = 1.6\times10^{19}$ m^{-3} , τ_E = 0.016 s (during ECRH) we obtain

$$P_{thr}^{START}(\mathrm{MW}) = 0.1\ (11 - z_n),\ \text{and}\ P_{thr}^{T\text{-}10}\ (\mathrm{MW}) = 0.08\ (11 - z_n) \tag{8}$$

For z_n = 4 (that is typical to ECRH in the L-mode) we obtain $P_{thr}^{T\text{-}10}$ = 560 kW. If we decrease $T_e(a)$ down to $T_e(a)$ = 0.05 keV and increase the density gradient up to z_n = 7 then the threshold power decreases by a factor of 4 down to P_{thr} = 160 kW. We see that the parameters $T_e(a)$ and z_n really control the L-H transition if the deposited power is comparable with the threshold power at z_n = 4.

Using the ITER scaling [6] $P_{thr}^{ITER} = 0.65\ n^{0.93}\ B^{0.86}\ R^{2.15}$(MW, 10^{20} m^{-3}, T, m), we obtain for the T-10 shot #26308 ($n = 0.16\times10^{20}$ m^{-3}, B = 2.4 T): P_{thr}^{ITER} = 570 kW, that is very close to our upper estimate 560 kW and for START P_{thr}^{ITER} = 9 kW in contradiction with experiment [2]. The scaling (7) for START at typical value of z_n = 6 gives P_{thr}^{START} = 500 kW, that is close to the Ohmic power.

4. Neutrals and edge plasma parameters

Figure 1 shows the calculated values of the edge neutral density N_a for 24 START shots. The experimental estimations of N_a for the plasma densities $n \sim 3$–4×10^{19} m^{-3} are $N_a \sim 10^{17}$ m^{-3} [2] that does not contradict our modelling. For T-10 shot #26308 with the plasma density $n \sim 2\times10^{19}$ m^{-3} the calculated neutral density is $N_a \sim (0.05\text{-}\ 0.1)\times10^{17}$ m^{-3} which is an order of magnitude less than for START at the same plasma density. The total neutral influx into the plasma in T-10 for these conditions is $\Gamma_n \sim (0.7 - 1.4)\times10^{21}$ part/s and $\Gamma_n \sim (3 - 5)\times10^{21}$ part/s for START.

We demonstrate the time evolution of plasma parameters during L-H transition on T-10 shot #26308. Its scenario shown in Fig. 2 is separated into 3 stages: the Ohmic (OH) (t<400ms), ECRH with L-mode (400<t<470 ms) and ECRH with H-mode confinement (470<t<790 ms). In experiment [7] at the time interval 400ms<t<450ms the edge density rises due to the enhanced diffusion over the whole plasma column that results in the increase of D_α signal. Then 20-30 ms before the transition the experimental edge temperature and density decrease [8]. Just before the L-H transition the D_α signal diminishes also. So our scenario for the boundary conditions $n(a)$, $T_e(a)$ and N_a (Fig.2) takes into account these peculiarities. As a result the threshold power P_{thr} decreases (7). After the transition the fast averaged density $\overline{n}$ rise and a steep density gradient at the plasma edge are observed (Fig. 3). It happens due to improvement of confinement only, as the neutral particles input flux became less than during the L-mode stage. The proposed scenario of the neutral density $N_a(t)$ (Fig. 2) allows us to describe by the CPTM both the behaviour of averaged plasma density through all of the 3 parts of shot and density profile in each of these parts (Fig. 3).

5. Plasma diffusion and heat conductivity

Now we compare the transport coefficients for the heat and particle transport. We introduce the «effective» diffusion and heat conductivities:

$$D^{eff} = -Q_n /(\partial n/\partial \rho), \quad \chi^{eff} = -(Q_e\text{-}3/2\ Q_n\ T_k) / (n\ \partial T_e/\partial \rho) \qquad (9)$$

and their ratio

$$\lambda = \lambda(\rho,t) = D^{eff}/\chi^{eff} \qquad (10)$$

Figures 4 and 5 shows the profiles D^{eff} and χ^{eff} for the H-mode plasma in START #36258 and T-10 #36208 shots. We see that transport coefficients in the gradient zone $0.3<\rho/\rho_{max}< 0.6$ for T-10 are 1.5-2 times less than for START despite that the magnetic field is $\times 8$ greater ($B^{T\text{-}10}/B^{START}$=2.4T/0.3T=8). But the difference in the edge transport is much higher. This can be explained by the influence of neutrals on the transport coefficients. Note that in order to describe the particle balance we took different numerical coefficients C for T-10 and START ($C^{T\text{-}10}$=0.7 and C^{START}=0.05). The value of λ is shown in Fig.6 for the same shots. This important parameter reflects the physics of the transport processes. The classical theory based on Coulomb collisions gives $\lambda = \lambda^{cl} = 0.2$. We see from Fig.6 that in tokamak plasma with anomalous transport for very different conditions of T-10 and START devices the parameter λ is not very far from the classical value.

6. Conclusion

The comparative transport analysis for T-10 and START H-mode shots shows the key role of boundary parameters in L-H transition in both devices. For START the convective heat losses caused by the high neutral source at the edge impede the H-mode appearance, for T-10 the influence of the is mainly seen on the n_a and T_a behavior that define the threshold power (7). The high value of the edge transport coefficients in START H-mode shot can indicate that the neutrals give a contribution to the transport coefficients. A similar value for the ratio λ was obtained on both tokamaks.

The paper is partially funded by the UK Department of Trade and Industry and Euratom through UKAEA Consultancy Agreement GQ 13158.

References

[1] Yu.N. Dnestrovskij et al, Proc. 26th EPS Conf., Maastricht, P4.109, p.178.
[2] A.Sykes et al., Phys. Rev. Lett., 84 (2000) 491.
[3] Yu.N. Dnestrovskij et al, Plasma Physics Reports, 23 (1997) 566.
[4] B.B. Kadomtsev, Sov. J. Plasma Phys, 13 (1987) 11.
[5] Yu.N. Dnestrovskij et al, Nucl. Fusion, **35**,1047 (1995).
[6] J.A. Snipes, Proc. 23th EPS Conf, Berchtesgaden, Pt.III, p.961.
[7] N.A. Kirneva et al., This conference, Rep. Or.026.
[8] G.S. Kirnev et al., This conference.

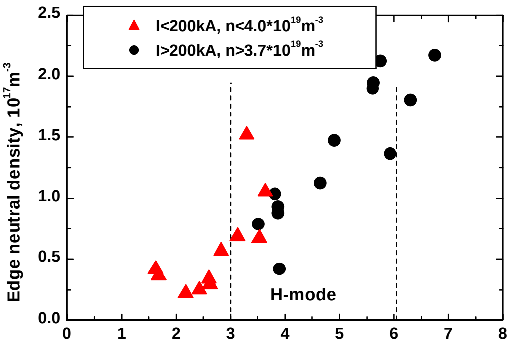

Fig. 1. The calculated edge neutral density versus plasma density in START.

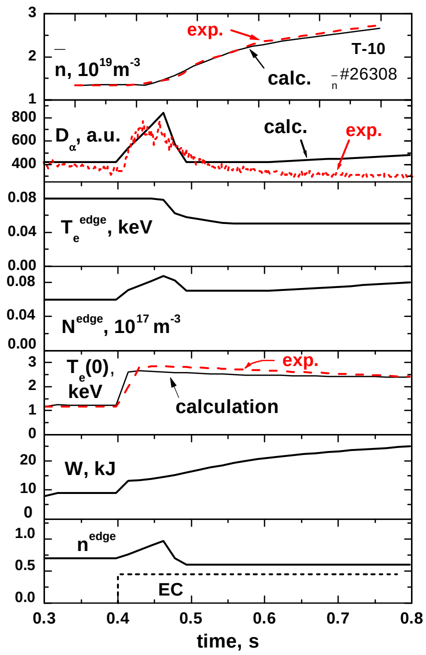

Fig.2. The scenario of T-10 shot26308 with L-H transition.

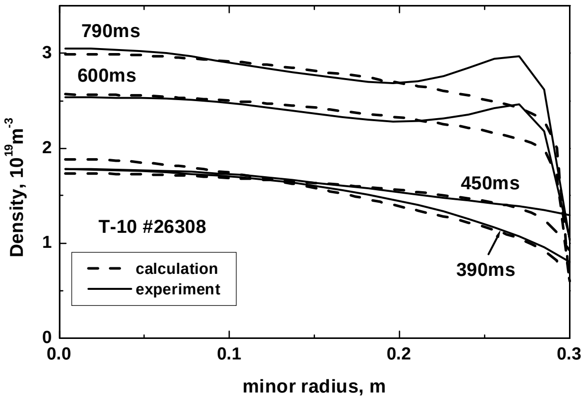

Fig.3. Experimental and calculated density profiles in T-10.

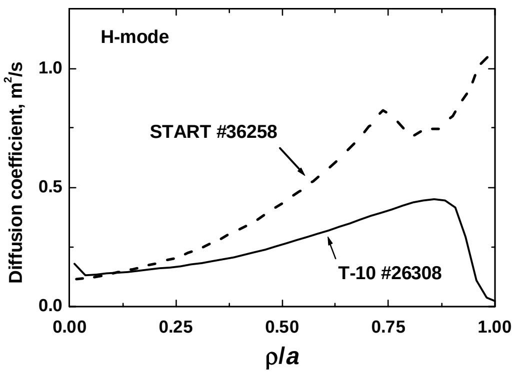

Fig.4. Effective diffusion coefficients for two shots from START and T-10.

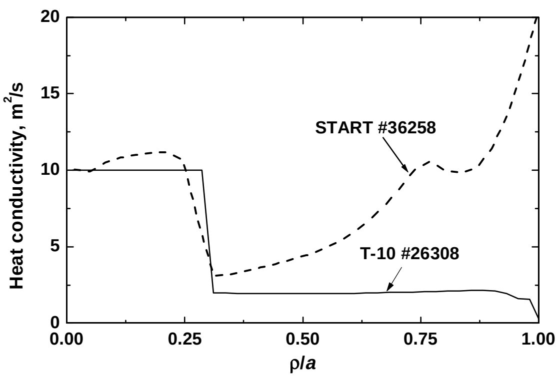

Fig.5. Effective heat conductivities for two shots from START and T-10.

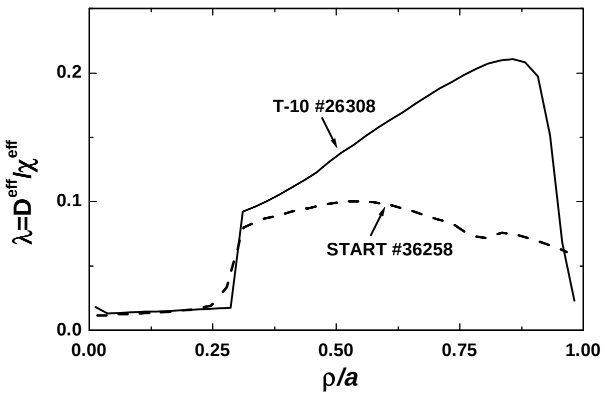

Fig.6. Ratio of diffusion coefficient to heat conductivity for two shots from START and T-10.