

EFDA-JET-PR(08)47

Yu.N. Dnestrovskij, A.Yu. Dnestrovskij, S.V. Cherkasov, A.V. Danilov, S.E. Lysenko, S.N. Gerasimov, T.C. Hender, I. Voitsekhovitch, C.M. Roach, M.J. Walsh, MAST and JET EFDA contributors

# Canonical Profiles Transport Model for H-mode Shots in Tokamaks

"This document is intended for publication in the open literature. It is made available on the understanding that it may not be further circulated and extracts or references may not be published prior to publication of the original when applicable, or without the consent of the Publications Officer, EFDA, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK."

"Enquiries about Copyright and reproduction should be addressed to the Publications Officer, EFDA, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK."

# Canonical Profiles Transport Model for H-mode Shots in Tokamaks

Yu.N. Dnestrovskij<sup>1</sup>, A.Yu. Dnestrovskij<sup>1</sup>, S.V. Cherkasov<sup>1</sup>, A.V. Danilov<sup>1</sup>, S.E. Lysenko<sup>1</sup>, S.N. Gerasimov<sup>2</sup>, T.C. Hender<sup>2</sup>, I. Voitsekhovitch<sup>2</sup>, C.M. Roach<sup>2</sup>, M.J. Walsh<sup>2</sup>, MAST and JET EFDA contributors\*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

<sup>1</sup>Russian Research Centre "Kurchatov Institute", Institute of Nuclear Fusion, Moscow, RF <sup>2</sup>EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK \* See annex of F. Romanelli et al, "Overview of JET Results", (Proc. 22<sup>nd</sup> IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).

Preprint of Paper to be submitted for publication in Nuclear Fusion

#### ABSTRACT.

The non-linear version of the Canonical Profiles Transport Model (CPTM), which includes both heat and particle transport equations, is used to simulate core and pedestal plasma for JET, and MAST H-mode shots. Simulations show reasonable agreement with experiment for both ELMy and ELM-free shots. RMS deviations of calculated results from the experimental ones are on the level 10-12% in main. The calculated ion and electron temperatures are very insensitive to the change of the deposited power profiles. The calculated pedestal temperature rapidly increases with plasma current; density profile peaking increases at low collisionalities.

# **1. INTRODUCTION**

It is well known that the temperature and pressure profiles in tokamaks are self-consistent [1-5]. The self-consistency of temperature profiles guided the construction of an equation for the heat conductivity in terms of so called "critical temperature gradients" [6-8]. In our previous works this critical gradient was expressed through the gradient of the canonical temperature profile [9, 10]. The self-consistency of pressure profiles allowed us to construct the particle flux similarly to the heat flux [4, 5]. In this report the proposed Canonical Profiles Transport Model (CPTM), which includes both the heat and particle transport equations, is used to simulate sets of JET, and MAST H-mode shots. We use the non-linear version of the CPTM, which simulates the evolution of profiles of plasma temperatures and density including their pedestals. The non-linear version is based on the so-called "forgetting effect", which leads to bifurcation in the transport equations. The bifurcation takes place, when the relative deviation of the calculated pressure gradient from the canonical one, in the vicinity of the plasma edge, exceeds some critical value. The boundary conditions for the region of the External Transport Barrier (ETB) is included in the model.

#### 2. BASIC EQUATIONS AND STATEMENT OF PROBLEM

The heat and particle fluxes,  $q_{\alpha}$  ( $\alpha = e, i$ ),  $\Gamma$ , are described by the following expressions:

$$q_{\alpha} = -n\chi_{\alpha}^{PC}T_{\alpha} \left(T_{\alpha}'/T_{a} - T_{c}'/T_{c}\right) H\left(-\left[T_{a}'/T_{a} - T_{c}'/T_{c}\right]\right) F_{a} - n\chi_{\alpha}^{0} T_{\alpha}' + 3/2 \Gamma T_{\alpha}$$
(1)

$$G = -D n (p_e'/p_e - p_c'/p_c) F_e F_i - D^0 n' + \Gamma^{neo},$$
(2)

where  $T_{\alpha}$  and *n* are the temperatures and density to be determined,  $T_c$  and  $p_c$  are the canonical profiles of temperature and pressure,  $\chi_{\alpha}^{PC}$  and *D* are stiffness coefficients,  $\Gamma^{neo} = n v^{neo}$ , H(x) is the Heaviside function,  $\rho$  is a radial coordinate ( $0 < \rho < \rho_{max}$ ), ' denotes the radial derivative. The values of  $\chi_{\alpha}^{PC}$  were found by the comparison of calculations with experiment [10, 11]:

$$\chi_{\alpha}^{PC} = C_{T\alpha} (1/M) (a/R)^{0.75} q(\rho = \rho_{max}/2) q_{cyl} (T_e(\rho = \rho_{max}/4))^{1/2} (3/R)^{1/4} (1/B_0) \bar{n}/n,$$
(3)

where *a* and *R* are minor and major radii,  $B_0$  is the toroidal magnetic field,  $q_{cyl}=B_0a^2/2I_pR$ ,  $I_p$  is the plasma current. The values of  $\chi_{\alpha}^{0}$  are much smaller than  $c_a^{PC}$ , but play an essential role inside the transport barriers. We set also [4, 5]  $D = C_n \chi_e^{PC}$ ,  $C_n = 0.08$ . This value of  $C_n$  leads to a reasonable range of the required cold neutrals influx  $q_N = (2 - 20) \times 10^{21} \text{ s}^{-1}$ , depending on plasma density and deposited power. We propose also that  $p_c \sim i_c$  and  $T_c'/T_c = 2/3 p_c'/p_c$ , where  $p_c$  and  $i_c$  are the dimensionless canonical profiles for pressure and current density. The derivation of the canonical profiles  $\mu_c=1/q_c$  and  $i_c$  was discussed in [5, 9]. We use everywhere in this work the following boundary condition for canonical profile:

$$\mu_{\rm c}(0) = (3.5 - 4)\,\mu_{\rm c}(a),\tag{4}$$

where the value of  $\mu_c(a)$  is defined by the solution of the equilibrium Grad-Shafranov equation. The foundations of a choice (4) will be discussed below.

It is proposed for density simulation that the evolution of the line-averaged density  $\overline{n}$  during the discharge is known. The transport model includes the subroutine adjusting the neutral particles influx from the wall  $q_N$  in order to keep the calculated averaged density equals to its experimental value.

In expressions (1)-(2),  $F_{\alpha} = \exp(-z_{p\alpha}^2/2z_0^2)$  is a "forgetting factor", where  $z_{p\alpha} = -(a \rho_{max}/\rho) (p_{\alpha}'/p_{\alpha} - p_{c}'/p_{c})$  is a dimensionless "distance" between the electron or ion pressure profiles and the canonical pressure profile. We suppose that a transport barrier occurs, when the distance  $z_{p\alpha}$  exceeds the second critical gradient  $z_0$ :  $|z_{p\alpha}| > z_0$ . To describe the H-mode, it is sufficient to set  $z_0 = 8$  [10, 11]. Note that in the transport barrier (the forgetting region)  $F_k << 1$  and the first terms in fluxes (1, 2) will be small, but outside this region  $F_k \approx 1$ .

To estimate the quality of simulation, we introduce the RMS deviations for temperatures:

$$d_2T = \{(1/N) \ \sum_{k}^{N} \left[ \frac{T_k^{calc} - T_k^{exp}}{T_k^{exp}} \right]^{1/2}$$
(5)

and a similar expression for density. The summation is produced over points inside the region  $0 < \rho < 0.8\rho_{\text{max}}$ , as the experimental data are less reliable near the plasma edge. As boundary conditions for temperatures and density we set  $T_{e}(a) = T_{i}(a) = 0.05 \text{keV}$ ,  $n(a) \sim n/10$ .

#### **3. SIMULATION OF JET ELMY H-MODE SHOTS**

The simulation is carried out for two groups of JET shots. The first group contains shots with a broad range of plasma current (Table 1), and was used in [12, 13]. The second group (Table 2) includes shots with small and large values of the collisionality parameter  $v_{eff}$ , which is proportional to  $n/T_e^2$ . Figure 1 shows the distribution of chosen shots in the  $(n, P_{tot})$  plane. We use in this section the experimental data as analysed using the TRANSP code.

To construct the transport barrier model, we have to specify the coefficients  $\chi_i^0$ ,  $\chi_e^0$  and  $D^0$ ,

which define the behaviour of plasma parameters inside the edge transport barrier (ETB). Model parameters were optimised for the chosen sets of shots to give:

$$\chi_i^0 = 0.23 P_{tot} / (\langle n \rangle I_p), \ \chi_e^0 = \chi_i^0 \{4.5 (T_e)^{1/2} / R\} [m^2/s]$$
 (6)

$$D^{0} = 0.4 \left( T_{e}(0) \right)^{1/2} / (\langle n \rangle R) \left[ m^{2} / s \right]$$
(7)

We use everywhere n,  $I_p$ ,  $P_{tot}$ , R,  $T_{e,i}$  and  $\chi$  in 10<sup>19</sup> m<sup>-3</sup>, MA, MW, m, keV, m<sup>2</sup>/s correspondingly, <...> denotes volume-averaging,  $P_{tot}$  is the total power deposited into plasma.

All parameters of the model are defined now and no free parameters remain. The chosen set of parameters will be used for description of the ELMy H-mode JET shots and all H-mode MAST shots. The change of parameters for the description of the ELM free H-mode JET shots will be discussed below. The quality of the simulation is displayed in figures 2 and 3, where the RMS deviations for electron and ion temperatures and density are shown. Figure 2 includes 10 shots from the first group. Figure 3 includes shots from both groups with plasma current  $I_p > 1.5$  MA.

The peaking of the electron temperature profiles (the ratio  $T_e(0)/T_e(0.5)$ ) for shots with  $I_p>1.4$  MA is shown in figure 4. It is seen that the most of points are in the narrow band  $1.3 < T_e(0)/T_e(0.5)$  < 1.6, and the peaking weakly decreases with increasing current. This means that the electron temperature profiles for different discharges are approximately similar, and, due to Ohm's law, the current density profiles are also similar. As a consequence, the ratio  $m_0/m_a$  is approximately constant. The calculations showed that  $\mu_0/\mu_a = 3.5 - 4$  and this is the equality we use in our choice of the parameter  $m_0$  in the canonical profile problem (4).

The electron-ion energy exchange power is high in the vicinity of the ETB due to low electron temperature. Therefore, the electron and ion temperature pedestals,  $T_{e,ped}$  and  $T_{i,ped}$ , are close to each other, and so for simplicity, we sometimes use  $T_{ped} = (T_{e,ped} + T_{i,ped})/2$  as the temperature pedestal. Figure 5 shows the calculated values of the temperature pedestal  $T_{ped}$  versus plasma current. The main tendency is clear: the values of  $T_{ped}$  increase with current rise. It may be explained by the decrease of temperature profile stiffness al low  $q_{cyl}$  (see Eq. (3)). Such behaviour of  $T_{ped}$  is usually observed in experiment.

In recent works [14-16], the peaking of the experimental density profiles in JET and ASDEX-U was considered. It was shown that in H-mode shots the peaking (the ratio  $n(0)/\langle n \rangle$ ) diminishes with increasing collisionality. Figure 6 shows the experimental and calculated density peaking factor versus collisionality for 10 JET shots with high current  $I_p > 1.5$  MA. The experimentally observed trend of the peaking factor increasing with decreasing collisionality is well reflected in the calculated results. It is caused in the model by the increase of the anomalous particle pinch as the collisionality diminishes.

The rise of calculated normalized density pedestal with collisionality for shots with plasma current  $I_p \ge 1.5$  MA is shown in figure 7. We conclude that a flattening of the density profile with

increasing  $n/T_e^2$  happens in parallel to the increasing importance of the density pedestal.

To estimate the reliability of the modelled density pedestal values, we temporarily relax constraint (7) and allow  $D^0$  to vary in some range as a free parameter. Figure 8 shows the dependences of  $n_{ped}$  and  $q_N$  on  $D^0$  with other parameters taken from Pulse No: 61174. Expression (7) gives us  $D^0 = 0.05$ . We see that the cold neutrals influx is proportional to  $D^0$ , but the density pedestal is really unchanged. This means that the density pedestal weakly depends on the transport barrier model, and that the modelled value of  $n_{ped}$  is robust. The physical explanation is that majority of the cold neutral influx (up to 90%) is absorbed inside the ETB.

The comparison of the experimental, calculated and canonical relative gradients of pressure is shown in figure 9. The experimental values in figure 9 are averaged over time intervals Dt ranging from 0.6 – 2s. The calculated values of  $R/L_p$  are very close to the experimental ones.

### 4. MODELLING OF ELM-FREE H-MODE JET PULSE NO'S: 41071 42623

These shots relate to the experimental campaign of 1997 with record fusion performance, but without tritium. They have the following features: (1) they are quite non-stationary; (2) during the ELM-free phase, which lasts 1.5-2.5s, the plasma current decreases by 10%, and the plasma line averaged density rises from  $\bar{n} = 2 \times 10^{19}$  to  $5 \times 10^{19}$  m<sup>-3</sup>. The model and experimental scenarios for density are shown in figure 10. The modelled time interval was 12 s < t < 13.7 s for Pulse No: 42623, and 12s < t < 14.7s for Pulse No: 41071. The NBI heating was switched on at t = 12 s and at the end of these time intervals there were giant ELMs (and so the calculations were stopped).

For the comparison of calculations with experiment we use in this section the "raw" experimental data for electron and ion temperatures and plasma density (and not data that were analyzed by TRANSP). To make clear the sensitivity of our calculations to the deposited power profiles, we use the following model. We fix the loss of hot particles to be 20%:  $Q_{abs} = 0.8 Q_{dep}$ , and assume that the fast ion density has a Gaussian radial profile  $n_{\rm hot} = n_{0,\rm hot} \exp(-\rho^2/2\lambda^2)$ . Here  $Q_{\rm abs}$  and  $Q_{\rm dep}$  are the absorbed and deposited powers, l is a parameter equal to a half width of the fast ion density profile. Comparing with calculations by TRANSP for ELMy shots in the previous section confirms that our choice of multiplier 0.8 in  $Q_{abs}$  is reasonable for shots with  $\langle n \rangle = (3-5) \times 10^{19} \text{ m}^{-3}$ , and suggests that I lies in the range 0.4 – 0.6. The power densities,  $P_{nbe}$ ,  $P_{nbi}$ , going from fast ions to the plasma electrons and ions were calculated using analytical expressions [17] and are shown in figure 11 for Pulse No: 42623. It is seen that in the plasma centre the local values of  $P_{\rm nbi}$  at  $\lambda = 0.4$  and 0.6 differ by a factor of 2. In the ELM-free discharges, the pedestals are quasi-steady-state and their absolute values exceed the time-averaged values of pedestals in the ELMy discharges by a factor of 3-4. The calculations have shown that to describe the temperature pedestals in the ELM-free discharges we have to diminish the heat diffusivities  $\chi_e^{0}$  and  $\chi_i^{0}$  by factor of 8–10 in comparison with (6, 7). This large factor arises due to the high stiffness of the temperature profiles. Figure 12 illustrates the dependence of the electron and ion temperature pedestals on the  $\chi_e^0$  and  $\chi_i^0$  for the Pulse No: 42623. Below in our calculations we reduce the constant multiplier 0.23 in (6) by a factor of 8-10

using the experimental estimates of the pedestal temperatures.

Calculated and experimental ion temperature profiles for Pulse No: 42623 are compared in figure 13. The experimental points are taken for three adjacent times spanning 75 ms. This allows one to estimate the scatter of experimental points. The calculated curves are drawn for  $\lambda = 0.4, 0.5$  and 0.6. It is seen that all calculated curves reasonably describe the experiment. This feature arises again due to the stiffness of the temperature profile. The experimental and calculated profiles of ion and electron temperatures for Pulse No: 41071 (with  $\lambda = 0.5$ ) are shown in figure 14. We see again the good accordance between experiment and model calculations.

The experimental and calculated plasma density profiles for Pulse No: 41071 at t = 14.5s are shown in figure 15. Note that these profiles are very flat. This feature is connected with a very fast density ramp up. The anomalous particle pinch in the model is too weak to peak up the density profile by moving particles from the edge to the plasma centre. This apparently also happens in the experiment as evidenced by the closeness of calculated and experimental profiles. Additional calculations have shown that a transition to a steady state scenario with saturated density leads to a density profile with higher peaking factor  $n(0)/\langle n \rangle \sim 1.3 - 1.4$ , which is close to the results shown in figure 6. for ELMy shots. Nevertheless, the steady state pressure profile in the model is close to the profile in the transient scenario. The peaking of density does not change the peaking of pressure. This feature has to be verified in future experiments.

The effective heat diffusivities defined by the formula  $\chi_{e,i}^{eff} = -q_{e,i}/(n dT_{e,i}/d\rho)$  are shown in figure 16. In the Pulse No: 42623 the deposited power is approximately two times larger than in Pulse No: 41071, so the heat diffusivity coefficients rise by approximately a factor  $2^{1/2} \sim 1.4$ . In the gradient zone  $\chi_{e,i}^{eff} \sim 2-3 \text{ m}^2/\text{s}$ , but inside the transport barrier these coefficients are lower by approximately a factor of 100. The transport barrier width is approximately 3–4% of minor plasma radius which does not contradict with experiment.

#### 5. SIMULATION OF MAST H-MODE SHOTS

To simulate the MAST H-mode shots we use the same parameters that were used for the modelling of the JET ELMy H-mode shots. Three MAST Pulse No's: 13026 and 13035 with  $I_p = 0.75$ MA,  $B_0 = 0.52$ T,  $P_{NB} = 1.8$ MW and Pulse No: 17466 ( $I_p = 0.74$ MA,  $B_T = 0.5$ T,  $P_{NBI} = 1.6$ MW) were chosen for modelling. All three shots are quite transient up to the moment  $t = t_{TS}$  of Thomson Scattering (TS) measurements. Figure 17 shows the time evolution of line-averaged density  $\bar{n}$  for chosen shots. At  $t = t_{TS}$  the values of density for Pulse No's: 13026 and 17466 are close to  $\bar{n} \sim 3.5 \times 10^{19}$  m<sup>-3</sup>, and the density ramp up is very high. In contrast, the value of density forPulse No: 13035 at  $t = t_{TS}$  is lower,  $\bar{n} \sim 2.5 \times 10^{19}$  m<sup>-3</sup>, and the rate of density ramp up saturates. In addition, the Pulse No's:13026 and 17466 demonstrate a rather long ELM-free phase just before the moment  $t = t_{TS}$ . In contrast, the Pulse No: 13035 is in ELMy H-mode (figure 18). The simulated electron temperature and plasma density profiles are presented in figures 19 – 20 in comparison with data from the 300-points TS system. Low value of  $B_0$  leads to high temperature profile stiffness (see Eq. (3)), and, as a consequence, to low values of temperature pedestal both for ELMy and ELM-free shots. The ELMfree shot demonstrates non-monotonic density profiles with so-called "ears" in the plasma periphery in the vicinity of ETB, in contrast with the ELMy H-mode flat density profile. Considered feature of density profiles is connected with rather specific form of particle pinch velocity profiles: the pinch velocities direction becomes outward in the outer half of minor radius (figure 21). This "antipinch" automatically appears in our model with pressure profile consistency. It counterbalances the diffusion in the region of "ears" with positive density gradient. As for the Pulse No: 13035, which corresponds to the ELMy H-mode and to the saturated density rise, the pinch velocity remains inward and close to the neoclassical value in the outer half of minor radius. The possibility of the outward direction of the pinch velocity is connected with adopted form of particle flux (2).

The results of the density profile simulation are rather different in the cases of ELMy and ELMfree H-mode. It may seem to be strange because the model equations (1)-(2) do not include any terms describing particle losses connected with ELMs. However, the full transport model adjusts the neutral particles influx from the wall in order to keep the central line-averaged density equal to its experimental value. For the Pulse No:13026, the acceleration of the experimental density ramp up occurs in association with the beginning of the ELM-free phase (see figures 17 and 18), while for the Pulse No:13035 the density ramp up rate saturates. Just at the time of ramp up acceleration, the transformation of density profile from flat to non-monotonic begins. It should be mentioned that this transformation is associated just with the increase of cold neutrals influx, but not with its absolute value. Additional runs with diminished values of  $D^0$  confirmed that the density profiles stayed practically unchanged in spite of smaller particle influxes.

#### CONCLUSION

The non-linear version of the CPTM has been applied to the modelling of JET and MAST ELMy and ELM-free H-mode shots. This version describes both the plasma core and the external transport barrier. It uses boundary conditions at the last closed magnetic surface and includes the possibility of bifurcations in the transport equations. Simulations have modelled the temperature and density pedestals reasonably well, and reproduce the main features of temperature and density profiles in H-mode shots. The electron temperature profiles have been found to be similar over a wide range of plasma currents in JET. This leads to similarity in current density profiles that is in contrast with the L-mode shots. The model describes also the sharp dependence of the temperature pedestal on plasma current. This dependence was observed earlier in many tokamaks. The model allows one to describe also the increasing density profile peaking with decreasing collisionality, as was marked before in several experiments. The key features of the MAST density profiles are also reproduced. It is notable that despite the wide variation in parameters and geometry between JET and MAST that the CPTM simulates both JET ELMy and MAST H-mode density profiles with precisely the same model.

# ACKNOWLEDGMENTS

The authors thank K.A. Razumova, P. Mantica, T. Tala and V. Naulin for useful discussions. The work is partly funded by the United Kingdom Engineering and Physical Sciences Research Council and by the European Communities under the contract of Association between EURATOM and UKAEA. The views and opinions expressed herein do not necessarily reflect those of the European Commission. This work was partly carried out within the framework of the European Fusion Development Agreement and Russian Grant RFBR 08-07-00182a.

# REFERENCES

- [1]. Coppi B. 1980 Comments Plasma Phys. Control. Fusion 5 261
- [2]. Kadomtsev B.B. 1987 Sov. J. Plasma Phys. 13 443
- [3]. Esiptchuk Yu.V. and Razumova K.A. 1986 Plasma Phys. Control. Fusion 28 1253
- [4]. Dnestrovskij Yu.N. et al 2006 Nucl. Fusion 46 953
- [5]. Dnestrovskij Yu.N. et al 2007 Plasma Phys. Control. Fusion 49 1477
- [6]. Dnestrovskij Yu.N. and Pereverzev G.V. 1988 Plasma Phys. Control. Fusion 30 47
- [7]. Rebut P.H., Lallia P.P. and Watkins M.L., Plasma Phys. and Control. Nucl. Fusion Research (Proc. 12th Int. Conf., Nice, 1988) IAEA, Vienna (1989) 2 191
- [8]. Ryter F. et al 2001 Plasma Phys. Control. Fusion 43 A323
- [9]. Dnestrovskij Yu.N. et al 2002 Plasma Phys. Rep. 28 887
- [10]. Dnestrovskij Yu.N., Dnestrovskij A.Yu. and Lysenko S.E. 2005 Plasma Phys. Rep. 31 529
- [11]. Dnestrovskij Yu.N. et al 1995 Nucl. Fusion 35 1047
- [12]. Voitsekhovitch I. et al 2006 Proc. 33rd EPS Conf. on Plasma Physics (Roma, 2006) 30I
   (ECA) P-1.078 and <u>http://epsppd.epfl.ch/</u>
- [13]. Dnestrovskij Y.N. et al 2007 Proc. 34th EPS Conf. on Plasma Physics (Warsaw, 2007) 31I (ECA) P-4.125 and <u>http://epsppd.epfl.ch/</u>
- [14]. Valovic M. et al 2004 Plasma Phys. Control. Fusion 46 1877
- [15]. Angioni C. et al 2007 Nucl. Fusion 47 L1-4
- [16]. Maslov M. et al 2008 Proc. 22nd Fusion Energy Conference (Geneva, 2008) EX/P5-20 and http://www-pub.iaea.org/MTCD/Meetings/FEC2008/ex\_p5-20.pdf
- [17]. Dnestrovskij Y.N. and Kostomarov D.P. 1986 Numerical Simulation of Plasmas. Springer-Verlag, Berlin.

Pulse No:	$I_p$ (MA)	$n, (10^{19} \text{ m}^{-3})$	P <sub>NB</sub> (MW)	$q_a$
61103	2.75	6.4	15	3.13
61138	2.5	10.4	14	3.66
61174	2.35	5.6	12	2.91
61132	2.35	2.3	2.5	3.16
61097	2	4.8	8	2.96
61366	1.5	2.9	14	4.27
61543	1.5	4.14	14	4.52
61520	1.4	3.1	14	6.3
61526	1	2.4	7.9	6.3
61236	1	2.3	12.5	11

Table 1. Parameters of JET shots from the first group.

Pulse No:	$I_p$ (MA)	$n, (10^{19} \text{ m}^{-3})$	P <sub>NB</sub> (MW)	$q_a$	$n/T^2$
62094	2.75	3.1	17.1	4.15	0.18
62093	2.75	4.1	25.1	4.22	0.25
68455	1.7	4.7	10.3	5.2	1.16
69463 ( <i>t</i> =22.8s)	1.7	5.3	8.2	5.2	1.43
69463 ( <i>t</i> =26s)	1.7	5	14.5	5.3	0.76

Table 2. Parameters of JET shots from the second group.



Figure 1: Main parameters of chosen JET H-mode shots, where  $P_{tot}$  is the total input power and n is the line-averaged electron density along a vertical central chord.



Figure 2: RMS deviations for the first group of shots.



1.8 Calculations 1.6  $T_{e}(0)/T_{e}(\rho = 0.5)$ П 뫄 1.4 B JET experiment 1.2 0.JG08.397-4c 1.5 2.5 2.0 I<sub>p</sub> (MA)

Figure 3: RMS deviations for 10 JET shots with current  $I_p > 1.5$ MA versus collisionality.

Figure 4: Peaking of experimental (red circles) and calculated (black squares) electron temperature profiles versus plasma current.



Figure 5: Calculated temperature pedestal versus current.



Figure 6: Experimental and calculated density peaking for shots with  $I_p > 1.5$  MA.





Figure 7: Calculated normalized density pedestal for shots with  $I_p > 1.5$  MA versus collisionality parameter.

Figure 8: Pedestal density n ped and cold neutrals influx  $q_N$ . as functions of particle diffusivity inside ETB.



Figure 9: Experimental, calculated and canonical relative pressure gradients at r = 0.5 for shots from the first group.



Figure 10: Temporal evolution of line-averaged model (solid lines) and experimental for Pulse No: 41071 (line with points) densities for JET ELM-free H-mode shots.



(2) (2)

Figure 11: Profiles of NBI power deposited to ions  $P_{nbi}$ and electrons  $P_{nbe}$  at different values of parameter  $\lambda$ .

Figure 12: Dependencies of the electron and ion temperature pedestals on the heat diffusivitiy  $\chi^0$  for JET shots.



Figure 13: The comparison of experimental ion temperature profiles from Pulse No: 42623 with calculated at different  $\lambda$ .



Figure 14: The comparison of experimental ion and electron temperature profiles from Pulse No: 41071 with calculated at  $\lambda$ =0.5.



*Figure 15: The experimental and calculated plasma density profiles.* 



Figure 16: The profiles of effective heat diffusivities.



Figure 17: Temporal evolution of line-averaged plasma density for MAST shots under consideration. Vertical dashed lines mark times of the TS measurements.



Figure 18:  $D_{\alpha}$  signal for MAST shots under consideration. Vertical lines mark the TS measurement times.



Figure 19: The experimental and calculated electron temperature (a) and density (b) profiles for MAST ELMy Pulse No: 13035.



Figure 20: The experimental and calculated electron temperature (a) and density (b) profiles for MAST ELM-free Pulse No: 13026.



Figure 21: Total and neoclassical pinch velocity profiles.