IAEA-CN-94/CT/P-02

A Two Term Model of The Confinement In Elmy H-Modes Using The Global Confinement and Pedestal Databases

ITPA H-Mode Database Working Group[1] and ITPA Pedestal Database Working Group[2] presented by J.G. Cordey[3] (e-mail: jgc@jet.uk)

[1]From Alcator C-Mod: J.A. Snipes, M. Greenwald; ASDEX/ASDEX Upgrade: F. Ryter, O.J.W.F. Kardaun, J. Stober; COMPASS-D/MAST/START: M. Valovic, A. Sykes, A. Dnestrovskij, M Walsh; DIII-D: J.C. DeBoo, T.N. Carlstrom; FTU: G. Bracco; JET/EFD A: E. Righi, J.G. Cordey, K. Thomsen, D. McDonald; JFT-2M/ JT-60U: Y. Miura, K. Shinohara, K. Tsuzuki, T. Fukuda, Y. Kamada, T. Takizuka, H. Urano; PBX-M/ PDX/ TFTR: S.M. Kaye, C. Bush; TCV: Y. Martin; TdeV: A. Cote, G. Pacher; TEXTOR: J. Ongena; TUMAN-3M: S. Lebedev; T-10: A. Chudnovskiy. [2]From Alcator C-Mod: A. Hubbard; ASDEX Upgrade: W. Suttrop, L.D. Horton; DIII-D: T.H. Osborne; ITER JCT: G. Janeschitz*, M. Sugihara; JT-60U: T. Hatae, Y. Kamada. [3]EURATOM-UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB, UK.

Abstract. Two different physical models of the H-mode pedestal are tested against the joint pedestal-core database. These models are then combined with models for the core and shown to give a good fit to the ELMy H-mode database. Predictions are made for the next step tokamaks ITER and FIRE.

I. Introduction

The ITPA Confinement and Pedestal Database groups joined forces in 1999 to assemble a common database of ELMy H-mode pulses containing both pedestal and core energy data. The analysis of preliminary versions of the database have been reported elsewhere [(1-3)]. The database has been recently strengthened with the addition of new data from JFT2M and MAST and further data from DIII-D and JET.

Two limiting models for the pedestal are tested against the data in section II, the first one is the “Thermal conduction Model” where the assumption is made that the main loss of energy from the pedestal is by thermal conduction down the steep temperature gradient in the edge region, and that the energy lost through the ELMs is small. In the other model which we refer to as the “MHD limit Model” it is assumed that the ELM loss is dominant and that the pedestal gradient is determined by an MHD stability limit. The main difference between the two models is that the thermal conduction model contains the loss power P. In section III the scaling of the energy in the core as a function of the global parameters I, B, P etc. is determined. Then in section IV, the two-term models derived in sections II and III are compared with the ELMy H-mode database. Finally in section V, predictions of the confinement time and the stored energy in the pedestal and core for the next step tokamaks ITER and FIRE are given.

II. Pedestal Scaling

The intersection of the pedestal database DB3v2 and the steady ELMy H-mode database DB3v11 gives rise to 443 observations from 7 tokamaks distributed as follows: ASDEX Upgrade (85), CMOD (19), DIII-D (90), JET (163), JFT2M (1), JT-60U (80) and MAST (5). The datasets from ASDEX Upgrade, DIII-D, JET and JT-60U contain both type I and type III

ELM data, whilst the JFT2M and MAST data is all type III ELM data and CMOD is mainly enhanced D_α mode data. To balance the unequal distribution of observations from each tokamak weighting factors wt are used as follows: JET wt = 1/3; AUG, DIII-D, JT60U wt = 1/2; CMOD wt = 1; MAST wt = 2; JFT2M wt = 4. Although the condition of the database is better than that used in previous analysis and the inclusion of the MAST data permits the aspect ratio scaling to be determined, there is still a strong correlation between the loss power P and the major radius R. Applying the Kadomtsev dimensional constraint in the fitting assists in controlling this correlation. We also fix the scaling with mass at the value in the IPB98 scaling ($\propto m^{0.2}$) since the mass is strongly correlated with size.

There are two energy loss mechanisms from the pedestal, one is thermal conduction down the steep edge gradient and the other is energy loss by ELMs, a simplified energy balance equation describing these processes is given below:

$$\dot{W} = P - \underbrace{\frac{W_{ped}}{\tau_{\varepsilon\,ped}}}_{\text{Thermal Conduction}} - \underbrace{g(\beta, \nu^*, \ldots)P}_{\text{ELM loss}} \qquad (1)$$

The definition of the pedestal and core energies is shown schematically in Fig.1. The total pedestal energy W_{ped} has been provided by DIII-D for a large number of observations, whilst for the remainder of the tokamaks only the electron energy W_{eped} is given for the bulk of their data. For these tokamaks, in this paper, we assume $W_{ped} = 2W_{eped}$, other assumptions have been tested and these will be discussed in a fuller paper. For those tokamaks in which no allowance has been made for the width of the pedestal, the effective volume is taken as $0.92 \times$ total volume as described in Thomsen et al[2].

a) Thermal conduction model

Here we assume that the dominant loss term is the thermal conduction term and assume that $\tau_{\varepsilon\,ped}\left(\equiv W_{ped} / P\right)$ is a function of the global variables I current (MA), R major radius (m), P thermal loss power (MW), n density (10^{-19} m^{-3}), B toroidal field (T), κ_a elongation, ε aspect ratio, m atomic mass and a shaping factor, F_q ($\equiv q_{95}/q_{cyl}$ here q_{cyl} is defined as $\frac{5\kappa_a a^2 B}{RI}$). In terms of W_{ped}, the best fit satisfying the Kadomtsev constraint is

$$\begin{aligned} W_{ped1} &= 0.00053\, I^{1.57 \pm 0.10}\, R^{1.41 \pm 0.13}\, P^{0.16 \pm 0.03}\, n^{0.05 \pm 0.04} \\ &\times B^{0.24 \pm 0.09}\, \kappa_a^{1.74 \pm 0.18}\, \varepsilon^{-2.13 \pm 0.28}\, m^{0.2}\, F_q^{2.46 \pm 0.19} \end{aligned} \qquad (2)$$

The RMSE of this fit (see Fig. 2) is 25.4% and it satisfies the gyro-Bohm constraint with $B\tau_{ped} \propto \rho_{ped}^{*-3}\, \beta_{ped}^{-4}$. The origin of the strong β scaling may be a consequence of the ELM losses. The quoted error on the exponents is one standard deviation which would be meaningful if all the observations were statistically independent, since this is unlikely to be the case, it is expected that the actual errors will be 3 or 4 times the ones given in Eq. (2).
Dropping the type III elm data reduces the RMSE to 21.3% and gives rise to a similar scaling expression,

$$W_{ped\,2} = 0.007\, I^{1.40 \pm 0.07}\, R^{1.69 \pm 0.11}\, P^{0.23 \pm 0.03} \times n^{-0.02 \pm 0.04} B^{0.56 \pm 0.08}\, m^{0.2}\, F_q^{\,2.09 \pm 0.18}\, \kappa^{0.88 \pm 0.02} \quad (3)$$

This result is similar to those of Kardaun et al [(1)] and Thomsen et al [(2)], the absence of Type I ELM data from MAST means that the aspect ratio dependence cannot be determined.

b) MHD limit model

In this model it is assumed that the ELM losses are dominant and that the pressure gradient in the pedestal is determined by an MHD stability limit due to ballooning or peeling modes with the gradient width Δ a function of the Larmor radius e.g. $\Delta \propto \rho_i^{\alpha} R^{1-\alpha}$. This implies that the pedestal β would have to be related to a function containing the dimensionless parameters ρ*, F_q etc. and then the energy in the pedestal would scale as $W_{ped} \propto RI^2\, f\left(\rho^*,\ F_q,\ m, \ldots\right)$.

Fitting the above to the pedestal database without the type III elm data gives

$$W_{ped\,3} = 0.054\, I^2 R\, \rho^{*0.38 \pm 0.06}\, m^{0.2}\, F_q^{1.23 \pm 0.22} \quad (4)$$

where ρ* is defined as $(T_{ped})^{1/2}/I$. The weak dependence on Larmor radius has also been seen in earlier treatments such as that by Takizuka et al.[(4)] and Thomson et al [(2)]. The RMSE of the fit is rather large 34%, it can be significantly reduced by the introduction of a further dimensionless parameter, the collisionality ν*.

III. The scaling of the plasma core

Turning to the confinement in the plasma core, we first subtract the pedestal energy W_{ped} from the total stored thermal energy to give the stored energy in the core W_{core}. Regressing W_{core} against the usual parameter set I, R, P, n, B, κ, m, ε using the full DB of 443 observations and imposing the Kadomtsev constraint gives

$$W_{core} = 0.12\, I^{0.88 \pm 0.08}\, R^{1.92 \pm 0.10}\, P^{0.26 \pm 0.02} \times n^{0.41 \pm 0.03}\, B^{0.16 + 0.07}\, \kappa_a^{0.49 \pm 0.16}\, \varepsilon^{1.36 \pm 0.18}\, m^{0.2} \quad (5)$$

with an RSME of 18.0%, the fit is shown in Fig. 3. This scaling, which has a Bohm like form, is similar to that of the L-mode scaling ITER96L[(5)]

IV. Comparison of the two term models with the ELMy H-mode database

The fits of sections II and III are now compared with the standard ITER-like data set (2783 observations from 11 Tokamaks) from the global ELMy H-mode database. As a bench mark, a fit is derived from the standard set for the core using first the Thermal Conduction Model for the pedestal Eq. (2), the fit has the form

$$W_{core\ fit\ 1} = 0.11\, I^{0.87}\, R^{1.94}\, P^{0.33}\, n^{0.46}\, B^{0.04}\, \kappa_a^{0.13}\, \varepsilon^{1.24}\, m^{0.25} \quad (6)$$

This expression in dimensionless variables scales as $B\tau_{\varepsilon\ core} \propto \rho^{*-2.3}\ \beta^{-0.8}$. The complete two term fit is shown in Fig. 4.

For the MHD limit pedestal model Eq. (4), we first re-express W_{ped} in terms of the pedestal density and then in terms of the line average density n, after using the formula $n_{e\ ped} = 0.7n$, which is found to be a good fit to the data in the pedestal database. The scaling of the core determined from the global ELMy H-mode DB has the form:

$$W_{core\,fit\,2} = 0.020\, I^{0.53}\ R^{2.51}\ P^{0.45}\ n^{0.69}\ B^{0.13}\ \kappa_a^{0.86}\ \varepsilon^{0.90}\ m^{0.18}. \qquad (7)$$

In dimensionless variables this has the form $B\tau_{core} \sim \rho^{*-3.0}\,\beta^{0.3}$, that is a gyro-Bohm form with slightly positive dependence on β. This particular two-term model is similar to those of Takizuka(4) and Thomsen(2).

Using the two models for the pedestal, Eq. (2) and (4), and the core models given by Eq. (5)-(7), we compare the fits of these two-term models to the standard ELMy H-mode set with that of the one term model, IPB92(y, 2), in Table I

Table I

Model		**RMSE(%)**	**ITER** τ_ε(s)	**FIRE** τ_ε(s)
a) One term IPB98(y,2)		15.8	3.66	0.94
Pedestal	**Core**			
b) Thermal Conduction Eq(2)	Eq. (6)	15.2	3.93	1.17
c) Thermal Conduction Eq(2)	Eq. (5)	15.7	3.70	1.16
d) MHD limit Eq (4)	Eq. (7)	15.9	3.86	1.00
e) MHD limit Eq (4)	Eq. (5)	18.3	2.74	0.75

The confinement time predictions for ITER (I=15MA, B=5.3T, $n=10\times10^{19}\ m^{-3}$, P=87MW, R=6.2m, ε=0.32, m=2.5, κ_a=1.75, F_q=1.5) and FIRE (I=7.7MW, B=10T, $n=48.5\times10^{19}\ m^{-3}$, P=34MW, R=2.14m, ε=0.28, m=2.5, κ_a=1.85, F_q=1.58), for the various models, are also given in Table 1. The three two term models b) - d) which are a good fit to the data give a confinement time which is within the 95% confidence interval of the IPB98 scaling. The energy in the pedestal for the Thermal Conduction model was 160MJ and the total thermal energy was 320MJ for ITER whilst the same parameters in FIRE were 23MJ and 39MJ respectively. The MHD Limit Model gives a significantly lower prediction for the energy in the pedestal 80MJ for ITER and 9MJ for FIRE.

V. Summary

The data in the joint-pedestal database has been fitted to two different types of models, the thermal conduction and MHD limit models. The two models give rise to a prediction for the pedestal stored energy in next step devices varying from 25% to 50% of the total stored energy. This uncertainty in the scaling of the pedestal is due to the condition of the pedestal database.

Using these pedestal models, three two term models have been developed which give a good fit to the ELMy H-mode database DB3v11. These three models give confinement time predictions for both ITER and FIRE which are close to those of the one term model.

References

[1] Kardaun, O.J.W.F. et al, IAEA-CN-77-ITERP/04, IAEA, Sorrento (2000).
[2] Thomsen, K. et al., Plasma Phys. Control Fusion, Vol. **44** pA429 (2002).
[3] Horton, L.D. et al., Plasma Phys. Control Fusion, Vol. **44** pA273 (2002).
[4] Takizuka, T. Plasma Phys. Control Fusion **40** (1998) 851.
[5] ITER Physics Basis Document, Nuclear Fusion **39** (1999) 2175.

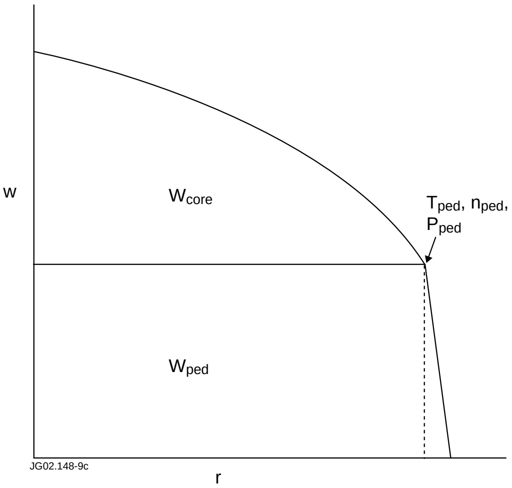

Fig. 1. Schematic diagram of the energy density versus radius, the energy in the pedestal W_{ped} and core W_{core} are marked.

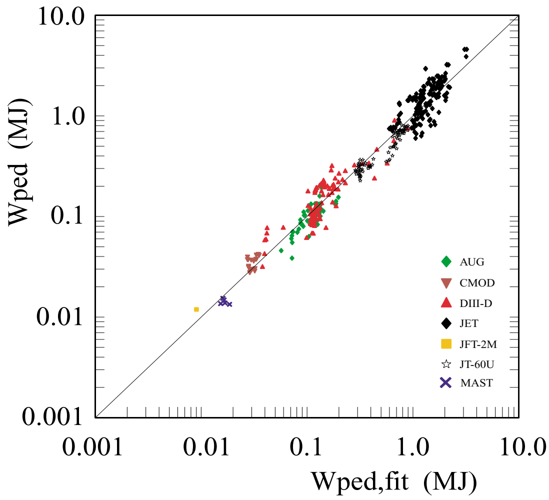

Fig. 2. W_{ped}(MJ) versus the scaling expression given by Eq. (2)

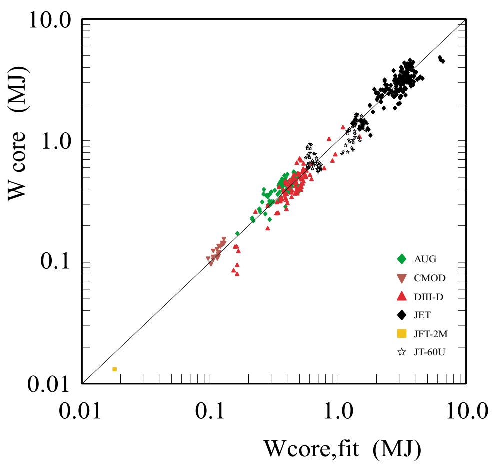

Fig. 3 W_{core}(MJ) versus the scaling expression given by Eq. (5).

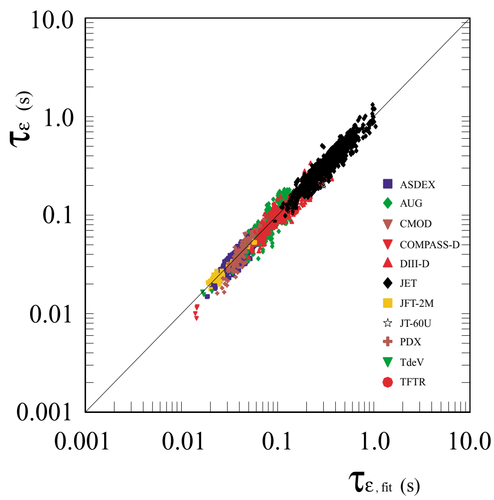

Fig. 4. τ_{ε} versus the best fit two term model i.e. the pedestal is given by Eq. (2) and the core given by Eq. (6).