Scaling of Thermal Energy Confinement in ASDEX Upgrade

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1. Introduction

The thermal confinement time of the ELMy H-mode is an important issue for ITER [J. G: Cordey: Confinement understanding and extrapolation to ITER, this conf.]. It is therefore of interest to investigate the confinement dependence in individual devices, as recently underlined [D. Campbell, Physics Issues in ITER, ASDEX Upgrade Seminar April 1997] . Such studies have the advantage of being free from machine to machine differences and the dependencies can be investigated in detail.

2. Experimental Data

2.1 Database: The database contains 140 time slices from 75 ASDEX Upgrade H-mode discharges taken during steady-state phases with regular type I ELMs. The selection includes only deuterium discharges heated with co-injected deuterium neutral beams. As a consequence, the atomic mass dependence will not appear in the results. Excluded are time slices with high radiation ($P_{rad}/P_{tot} < 45$ %) - for instance induced by impurity injection - , with transient behaviour and near the ß-limit . Only discharges with deuterium gas puffing to vary the density have been selected.The plasma configuration was a single null with the ion gradB drift direction pointing towards the x-point in the standard geometry of ASDEX Upgrade R = 1.65 m, a = 0.5 m , κ = 1.7 and upper triangularity from 0 to 0.1. Geometrical dependencies are therefore not included in the derived scaling. The discharges were performed with boronized walls. The database combines operation periods with the divertor I equipped with carbon- (1995) and tungsten tiles (1996). The range of the main plasma parameters covered by the data base are indicated in Fig. 1. The Correlation Matrix of the database gives Table I.

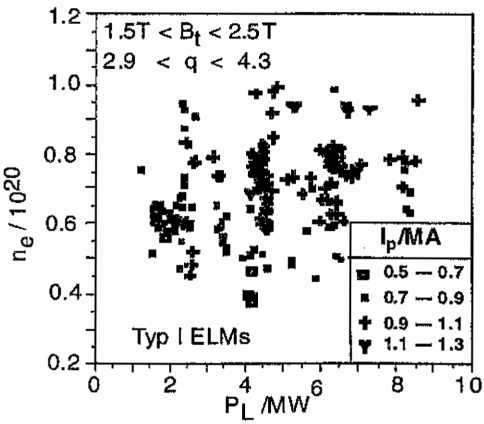

Fig.1: Database for the scaling

2.2 Recovery of neutral beam heating data: In order to evaluate thermal confinement data of neutral beam heated discharges the heating power coupled to the plasma as well as the energy content of the fast ions have to be determined from the neutral power injected into the torus. Monte Carlo techniques are used for this purpose but due to the extrememly high CPU-times such codes are not practicable for a shot by shot analysis. A much faster method now available for ASDEX Upgrade plasmas is based on Function Parametrization of a statistically well designed database generated by several hundreds of runs of the Monte Carlo code FAFNER. However, plasma density and temperature profiles are required as an input, which are not always available for ASDEX Upgrade discharges.

Variable	p_{Div}	P_T	I_p	n_e	B_t
P_{Div}	1	0.49	0.44	0.63	0.31
P_T	0.49	1	0.42	0.23	0.23
I_p	0.44	0.42	1	0.52	0.69
n_e	0.63	0.23	0.52	1	0.05
B_t	0.31	0.23	0.69	0.05	1

Table I Correlation matrix of the database for the AUG typ I ELM discharges

In order to provide the fast ion losses and the energy content of the fast beam ion population for almost each of the ASDEX Upgrade discharges a fit procedure has been derived based on five plasma parameters readily available for most of the shots: line averaged density n_e separatrix density $n_e(a)$, SOL density fall-off length $\lambda_{n,SOL}$, total plasma energy content W_{mhd}, and plasma volume V_p. A subset of the FAFNER results produced for the Function Parametrization was used to find the following fit formulae for 60 kV D^0 beams:

Shinethrough: $\exp(-n_e/\alpha_i)$ Ripple Losses: η_i

Re-ionization in SOL: $\beta_i * (n_e(a) * \lambda_{n,SOL})$ Charge exchange losses: $\gamma_i * (\tau_{sd})^{\delta_i}$

Orbit Losses: $\varepsilon_i * (n_e(a) * < T_e >)^{\nu_i}$ Fast ion content: $\kappa_i * (\tau_{sd})$

where $\tau_{sd} = f(n_e, <T_e>)$ is the fast ion slowing down time and $<T_e>$ is estimated from the measured value of W_{mhd} by $<T_e> = (1/3) * W_{mhd} / (n_e * V_p)$. The coefficients ($\alpha_i, \ldots; i = 1, \ldots, 4$) have been determined individually for each of the four ion sources of the ASDEX Upgrade neutral beam injector. The ripple losses are only significant for the two ion sources injecting more perpendicularly and are calculated to be about 7% with neglegible dependence on edge parameters.

3. Thermal confinement scaling

For the described dataset we analyse the thermal confinement time. In our case of neutral beam heated plasma and time slices with stationary plasma energy content the thermal confinement time τ_{th} is calculated from

$$\tau_{th} = (W_{MHD} - W_{FAST\ IONS}) / P_L \quad \text{with } P_L = P_{OHM} + P_{INJ} - P_{LOSSES}$$

where the plasma energy W_{MHD} is corrected by the energy of the fast beam ion population $W_{FAST\ IONS}$. P_{LOSSES} represents all the fast ion losses. P_{LOSSES} and $W_{FAST\ IONS}$ are calculated by the fit procedure described above. Radiation losses are not taken into account, since the power radiated within the separatrix is in the order of only 15%. For the analysis by linear regression we use a power law assumption for the thermal confinement :

$$\tau_{th} = A * I_p^{\alpha_I} * P_L^{\alpha_P} * n_e^{\alpha_n} * p_{div}^{\alpha_{div}} \quad [s, MA, MW, ne10^{19}\,m^{-3}, P]$$

with the dependencies: Plasma current I_p, absorbed heating power P_L, line-density n_e and divertor neutral gas pressure p_{Div} .The gas pressure measured in the divertor region has been included because a pronounced influence of gas pressure on confinement has been found [1] , [5]. The gas pressure in the divertor is probably not the physical cause of the observed degradation but rather its influence on the edge parameters [2] . Pressure measurements in the main chamber could also be used, but the data in divertor are more complete and reliable. Pressures measured in main chamber and divertor are generally tightly coupled. The influence of the toroidal field is found to be low and could not be determined with reasonable precision from the database. The B_t dependence is therefore set to zero in the following analysis. This is roughly compatible with single shot to shot observations.

A regression has been performed including simultaneously the four above variables and the result are given in Table I. In spite of the size of the data base and the covered parameter range, the dependencies provided by the simultaneous regression might not be reliable, because of the correlation within the data (see Table II). Therefore a "regression by step" analysis has been performed as well, by windowing the database into fictive scans in which only one variable is varied whereas the other 3 are kept constant as much as possible. First the dependence on the divertor pressure is obtained from a scan at constant plasma current (Ip =1 MA) and narrow intervals for the density and the total heating power. The analysis is summarised in Table III, which gives the single regression steps and the parameter intervals used. The resulting dependence exponents are also given in Table I.

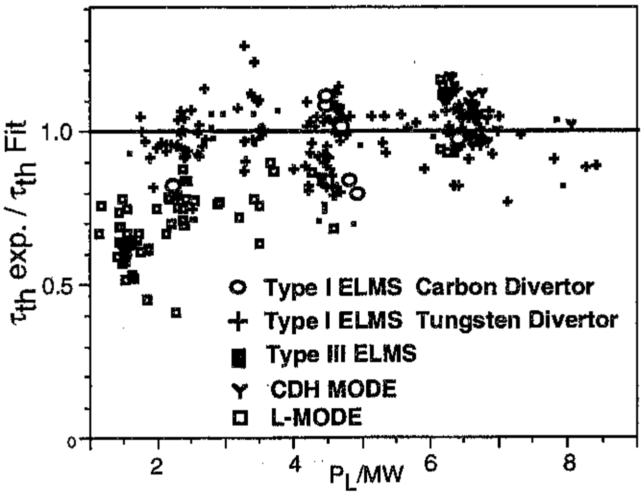

Fig.2: ASDEX Upgrade thermal confinement normalised by the scaling ("regression by step)"

The scaling provided by the "regression by step" is illustrated in Fig.2 where thermal confinement time normalised by the derived scaling is plotted versus the total input power P_L for the time slices of the database. The data are reasonably well represented with a standard deviation of 10%. For comparison, Fig.2 also includes data from other confinement regimes currently observed in ASDEX Upgrade. Discharges with type III ELMs do not significantly differ from the type-I ELM fit. The thermal confinement of the L-mode approaches the H-mode confinement for higher P_L which is related to higher densities in our database. The CDH-mode points clustering around P_L=6.5 MW tend to slightly higher thermal confinement compared to the scaling. This is attributed to the density peaking caused by edge radiation which compensates the confinement degradation correlated by the required high divertor pressure.

4. Discussion

The majority of the data represent the operation of ASDEX Upgrade with the tungsten divertor in 1996. Only a few data points refer to the carbon divertor because of missing data for the divertor pressure. However no influence on the confinement appears for the operation with the two different materials in the divertor, in agreement with previous results [3].

Our results can be compared (Table II) to the thermal ELMy scaling obtained with the ITER H-mode database (ITER-92-P(y)) and recommended by the by ITER Modeling and Database Expert Group. [4]. A basic difference between the two expressions is that the neutral pressure is not included in the ITER-92-P(y) scaling. However this is not expected to have a major influence because most of the ELMy data included in the ITER database were not obtained with strong gas puffing but rather at the natural density for each device. The two scalings yield very similar dependencies for Ip, Bt. The difference on the density dependence might be attributed to the neutral gas pressure. In fact, the difference in the exponents is consistent with this assumption. The difference in the heating power exponent is outside the uncertainties.

Scaling	A	α_I (+/-)	α_P (+/-)	α_{Bt} (+/-)	α_n (+/-)	α_{div} (+/-)
AUG linear regression	0.21	0.59(0.08)	-0.53 (0.08)	(0)	0.5 (0.08)	-0.13 (0.02)
AUG lin. regress. "by steps"	0.19	0.85 (0.08)	-0.55 (0.05)	(0)	0.5 (0.05)	-0.2 (0.02)
ITER H-mode Database [4]	0.034	0.9	-0.65	0.05	0.3	(0)

Table II: Power law coefficients for thermal confinement scalings

Response	Variable	Parameter Range used for Regression
τ_{th}	P_{Div}	I_p = 1 MA / 7.5 < $n_e/10^{19}$ < 8.5 / 6.1 < PT/MW < 6.9
$\tau_{th} / P_{Div}^{-0.2}$	P_T	I_p = 0.8MA / 5 < $n_e/10^{19}$ < 7 / 0.05 < P_{Div}/ Pasc.<0.3
$\tau_{th} / P_{Div}^{-0.2} \cdot P_T^{-0.55}$	I_p	6 < $n_e/10^{19}$ < 8
$\tau_{th} / P_{Div}^{-0.2} \cdot P_T^{-0.55} \cdot I_p^{0.85}$	n_e	

Table III : Sequence of the Regression by Steps

This question must be addressed in further work because it has a dramatic effect on the projection to ITER with 300 MW heating power.

Reference

[1] F. Ryter IAEA-CN-64-/AP1-5 1996 Montreal

[2] W. Suttrop / his conference

[3] R. Neu et al Plasma Phys. Control. Fusion38 1996 A165

[4] IAEA-CN-56/F-1-3 /1992/ H-Mode Database Working Group (Pres. O. Kardaun)

[5] O. Gruber / this conference