EDGE DATABASE ANALYSIS FOR EXTRAPOLATION TO ITER

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Abstract

An edge database has been archived to facilitate cross-machine comparisons of SOL and edge pedestal characteristics, and to enable comparison with theoretical models with an aim to extrapolate to ITER. The SOL decay lengths of power, density and temperature become broader for increasing density and q_{95}. The power decay length is predicted to be 1.4-3.5 cm (L-mode) and 1.4-2.7 cm (H-mode) at the midplane in ITER. Analysis of Type I ELMs suggests that each giant ELM on ITER would exceed the ablation threshold of the divertor plates. Theoretical models are proposed for the H-mode transition, for Type I and Type III ELMs and are compared with the edge pedestal database.

1. INTRODUCTION

The physics design of ITER requires a reliable estimate / prediction of the H-mode pedestal, SOL and divertor plasma parameters. These parameters can be obtained by several routes, namely by scaling laws based on the experimental H-mode pedestal and SOL databases or by theoretical models validated by the databases above. The physics understanding of the H-mode pedestal is the key for characterising the confinement and stability of the core plasma, while SOL and divertor physics implemented into models guides the divertor design. In this paper we report results from the edge database analysis[1-5].

2. SOL DATABASE ANALYSIS

Scaling laws derived from the SOL database for Ohmic and L-mode discharges yield a power decay length which decreases with power and increases with density, q_{95} and the device size [1].

• Scaling L-1 (with measured divertor power) (Fig. 1) :

$$\lambda_q^{L-1}(m) = (6.6 \pm 2.2)10^{-4} R(m)^{1.21\pm0.15} P(MW)_{div}^{-0.19\pm0.05} q_{95}^{0.59\pm0.11} \bar{n}_e(10^{19}m^{-3})^{0.54\pm0.15} Z_{eff,scal}^{0.61\pm0.09}$$

• Scaling L-2 (with total input power) :

$$\lambda_q^{L-2}(m) = (7.2 \pm 2.4)10^{-4} R(m)^{1.21\pm0.15} P(MW)_{TOT}^{-0.28\pm0.08} q_{95}^{0.59\pm0.11} \bar{n}_e(10^{19}m^{-3})^{0.68\pm0.16} Z_{eff,scal}^{0.65\pm0.09}$$

This can be understood if the transport in the plasma edge and the SOL is Bohm-like.

Scalings derived for H-mode discharges show a broadening of the power deposition profile with increasing power and q_{95}.

• Scaling H-1 (with measured divertor power) :

$$\lambda_q^{H-1}(m) = (5.2 \pm 1.3)10^{-3} P(MW)_{div}^{0.44\pm0.04} B(T)_{\phi}^{-0.45\pm0.07} q_{95}^{0.57\pm0.16}$$

• Scaling H-2 (with total input power) :

$$\lambda_q^{H-2}(m) = (5.3 \pm 1.4)10^{-3} P(MW)_{TOT}^{0.38\pm0.04} B(T)_{\phi}^{-0.71\pm0.08} q_{95}^{0.30\pm0.15}$$

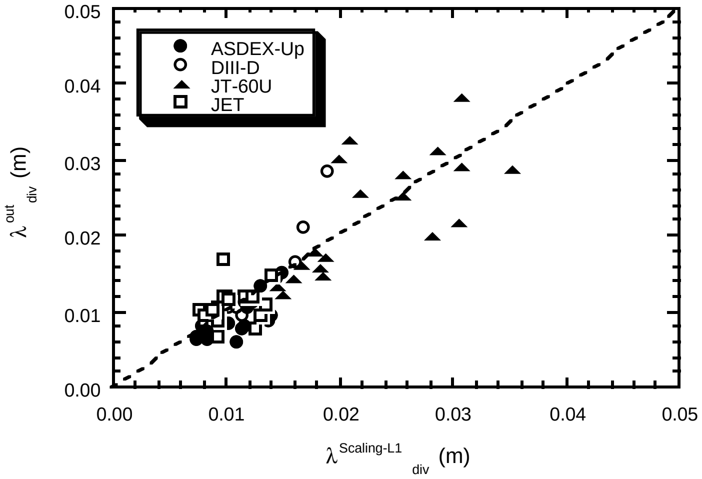

FIG. 1. Measured outer divertor power width for Ohmic and L-modes versus scaling law L-1

The extrapolation of the above scalings to the ITER-EDA machine (R = 8.14 m, I_p = 21 MA, B_T = 5.7 T, q_{95} = 3.0, Z_{eff} =1.8) are given in Table 1, where the magnetic and divertor geometry of ITER have been taken into account. The values obtained for ITER show that the scaling would yield power levels that fall within reasonable engineering limits. The scaled peak power is ~ factor 2 lower than 2 D code results [6], i.e. the transport chosen for the modelling is more conservative.

TABLE 1: EXTRAPOLATION OF POWER DECAY LENGTH TO ITER

Regime	$<n_e>$ (10^{19} m^{-3})	P_{net} (MW)	P_{div} (MW)	λ_q (cm)	$P_{\|\|}^{peak}$ (MW/m^2)	P_{div}^{peak} (MW/m^2)
L-mode (L-1)	5.0	100	40	$2.7 \binom{+0.8}{-0.8}$	$61 \binom{+26}{-14}$	$2.2 \binom{+0.9}{-0.5}$
L-mode (L-2)	5.0	100	40	$2.1 \binom{+0.9}{-0.7}$	$79 \binom{+40}{-24}$	$2.9 \binom{+1.5}{-0.9}$
H-mode (H-1)	10.0	200	50	$2.5 \binom{+0.2}{-0.2}$	$83 \binom{+7}{-6}$	$3.0 \binom{+0.3}{-0.2}$
H-mode (H-2)	10.0	200	50	$1.6 \binom{+0.2}{-0.2}$	$129 \binom{+18}{-14}$	$4.7 \binom{+0.7}{-0.5}$

A comparison of the systematic behaviour of λ_{ne} and λ_{Te} has been performed among all major tokamaks [2]. Phenomenologically, the analysis is divided into two different OH-L regimes: "high recycling" (T_{es}<40-60eV) where the widths increase rapidly with decreasing T_{es} and "low-recycling" where variations are more subtle. For high recycling regimes one finds $\lambda_{Te} \sim T_{es}^{-(1.3-2)}\, q_{95}^{(0.6-1.4)}\, P_{tot}^{(0.5-0.9)}$. For low recycling regimes the baseline behaviour for all machines is reasonably described as: $\lambda_{Te}(min) \sim 15(S_{area}/I_p)^{0.7}$ and $\lambda_{ne}(min) \sim 10.5(S_{area}/I_p)^{0.7}$. For ITER(OH-L) the predictions are: λ_{ne}(min) ~ 1cm and λ_{Te}(min) ~1.5cm. Larger values will be obtained for high q_{95} or P_{tot}, or when n_e approaches the GW limit.

An $n_{e\text{-}sep}$ analysis of OH and L-mode discharges yielded the following power law [3]

$$n_e(sep)=0.00236\ \overline{n_e}^{\,1.08}\ k^{1.11}\ B_T^{0.78}$$

where k is the plasma elongation. From this scaling, the separatrix density in ITER is predicted to be $3.0(\pm 0.7)\times10^{19}$ m^{-3} in L-mode with gas fuelling at $n_{e\text{-}core} \sim 5.10^{19}$ m^{-3}.

The 2-D B2-EIRENE code calculations performed for several existing machines were compared with plasma edge parameters archived in the edge profile database[4]. H-mode discharges of DIII-D and JET can be satisfactorily modelled with similar values of the transport coefficients, when the power flow into the SOL is dominated by the ion channel.

Analysis of the ITER ELM database indicates that the ELM energy is 2-6% of the plasma stored energy. In terms of edge parameters the ELM energy represents ~36% of the pedestal electron energy in DIII–D and ~26% in JET[5]. The pedestal electron energy is given by the value of the electron pressure, at the top of the steep gradient region just inside the separatrix, multiplied by the entire plasma volume inside the separatrix. The above fraction remains nearly constant, over a wide range of main plasma parameters. Given ITER's proposed operating parameters density, plasma volume and expected scaling of the edge pedestal, this would represent an ELM energy of approximately 25 MJ if the same fraction of pedestal energy were lost in ITER as was found in DIII–D and JET. The large Type I ELMs typical for a low recycling H–mode may therefore exceed the divertor target ablation threshold by a factor of 5. This constraint implies a regime where either the ELM energy is a smaller fraction of the edge pedestal energy, or a regime with a smaller edge pedestal that still maintains good confinement or a different type of ELM (i.e. Type II). Such regimes have been achieved on several machines, e.g., on JET, encompassing high densities with gas puffing, with use of RF heating and operation with Type III ELMs, grassy ELMs on DIII-D, minute ELMs (Type II) on JT-60U, ENHDA on C-MOD, CDH mode on ASDEX-U. However, except for CDH all these regimes were obtained with high triangularity discharges (e.g. ~ 0.5 measured at the separatrix).

3. H-MODE PEDESTAL DATABASE ANALYSIS

The most important data archived in this database are the electron temperature and density at the top of the H-mode pedestal, measured during different phases of the discharge (L to H-mode transition, Type III ELMs, Type I ELMs, e.t.c.). $T_{e\text{-}ped}$ plotted against $n_{e\text{-}ped}$ obtained during different phases of the discharge defines boundaries for the various regimes (edge operational space diagram, Fig. 2a). We propose a set of unified theoretical models which are able to describe these boundaries in the database in order to extrapolate to ITER.

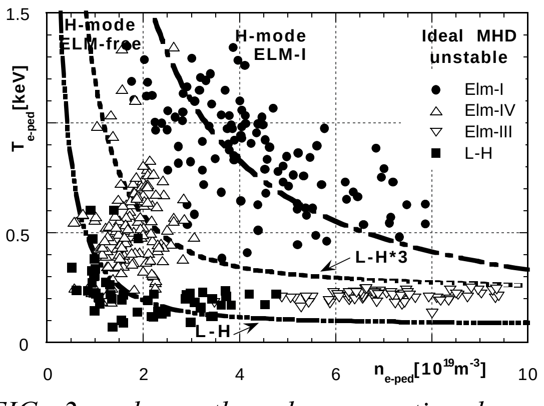

FIG. 2a: shows the edge operational space diagram for DIII-D. Shown are H-mode transition data, Type III , Type IV and Type I ELMs as well as theoretical curves defining the boundaries for these regimes.

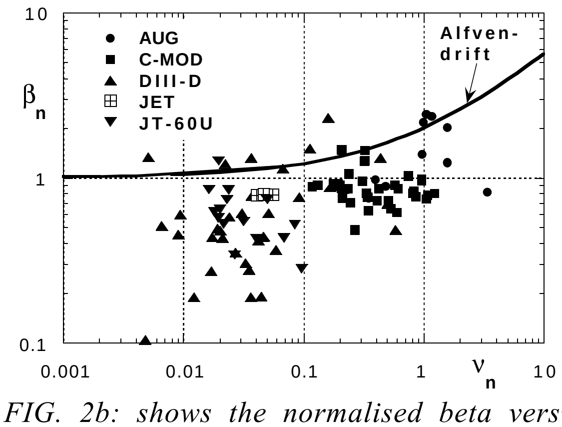

FIG. 2b: shows the normalised beta versus normalised collisionality for several divertor tokamaks at the top of the H-mode pedestal prior to the L-H transition as well as the threshold defined by the Alfven drift theory.

H-mode transition: We examined several theories for the H-mode transition (e.g, Alfven drift instability [7], drift-ballooning mode stabilisation [8], and mode suppression by electric field shear only) by comparing them to the edge pedestal database. In addition a data analysis to derive the H-mode transition scaling in terms of non dimensional parameters, ρ^*, ν^* and β, evaluated at the plasma edge was also performed. So far, the Alfven drift turbulence suppression model [7] as well as a more elaborate numerical model based on drift ballooning modes [8] has been identified to reproduce the LH transition boundary reasonably well. The essential hypothesis of both models is the suppression of electron turbulence when exceeding a critical beta value on the plasma edge. The stabilisation of the drift Alfven modes can be characterised by two normalised parameters, i.e. the normalised plasma beta and the normalised collision frequency. The suppression occurs when the normalised beta in the pedestal region is greater than a critical value, i.e. $\beta_n > \beta_{crit} = 1 + \nu_n^{2/3}$. The measured LH transition points on the β_n - ν_n plane are shown in figure. 2b for different machines together with the transition boundary defined by the Alfven-drift theory [8] showing reasonable agreement.

Type III ELMs: The general trend of the Type III ELM data agrees reasonably well with the H-mode transition curve multiplied by factor 2 to 3 (Fig. 2a). So far no satisfactory theoretical model has been found for Type III ELMs.

Type I ELMs: The type I ELM boundary is defined by the MHD stability (e.g. ballooning or kink modes) and thus follows a constant pressure curve. The effects of the separatrix, the X-point and the finite edge current density of ITER-relevant current and pressure profiles, which modify the stability properties of such modes are investigated. Again the models above are compared with the edge pedestal database using a scaling of the pedestal width also derived from the database which depends on machine size. For Type I ELMs, we fit the measured pedestal widths assuming $\Delta = f\sqrt{\rho_{pol}(T_{Sep})R}$ with $f \approx 0.134\ R^{0.96}$ [9]. This predicts a width of ~ 15 cm for ITER where the poloidal gyro radius is evaluated at the separatrix. Because Tsep varies only weakly with plasma parameters Δ_{ped} ~ const and therefore $p_{tot-ped}$ = constant is reproduced as observed for Type I ELMs. The strong scaling with machine size and weak dependence on ρ_{pol} suggests that MHD edge stability requirements may play a major role in determining the edge pedestal width. The width may be related to the region where the magnetic shear is high enough to support large pressure gradients, i.e. where p_{crit} is large. This conjecture is consistent with the very sharp increase in shear observed between $\psi_{95\%}$ and the separatrix when the bootstrap current is included. It is also consistent with the difference in the pedestal widths for Type I ELM discharges (6 cm) and for ELM free discharges (4 cm) observed in JET [10]. The models describing the various boundaries in the edge operational space diagram were implemented in a 1.5 D code in order to test their time dependent behaviour, results are reported in [11].

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