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Energy Confinement in ELMy H-mode on MAST

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Introduction

Data from the low aspect ratio tokamak MAST are extending International Tokamak Databases from medium sized devices by a factor of two in plasma aspect ratio. These data are imposing powerful constraints on dependences of heat transport on dimensionless parameters. In addition, MAST data are making the databases more symmetric around the ITER point along the aspect ratio axis and thus improving the predictive capability ofscalings towards ITER. H-mode plasmas from low aspect ratio tokamaks START, MAST and NSTX have been described earlier [1, 2, 3]. This paper reports on dedicated experiments on MAST aimed to extract data compatible with International Databases and discussion of their effects on tokamak scalings.

Power threshold for ELMy H-mode plasmas

In MAST, transition from L-mode to H-mode is typically accompanied by continuous ELM activity (type-III ELMs) and thus the L-H transition also represents the boundary for the ELMy H-mode regime. The L-H transition boundary has been mapped using ohmically heated plasmas in pure deuterium and with a double null magnetic configuration and inboard gas puffing [4]. Ohmic heating leads to a slow L-H transition allowing good representation of power and density at the transition because these quantities evolve slowly. The double null configuration was chosen because it has the lowest threshold under these conditions [5]. Data were taken from a density scan at fixed toroidal magnetic field, $B_T\approx0.4$T (vacuum field at magnetic axis), plasma current $I_p\approx0.6$MA, major radius $R\approx0.75$m, minor radius $a\approx0.52$m ($\varepsilon_{MAST}=a/R=0.68$) and elongation $\kappa\approx1.9$. Fig. 1 shows the data compared with one of the recent scalings [6]. The MAST data are on average a factor of $P_{th,MAST}/P_{scal}\sim1.7$ above the scaling prediction. If one assumes that the difference between the scaling and the MAST data is due to the ε-dependence (and not due to other factors such as the difference between single and double null configuration, plasma shape or heating method) then the MAST data introduce a weak dependence of threshold power on inverse aspect ratio $P_{scal}(\varepsilon)\propto\varepsilon^y$ with the exponent of the order of $y\sim\ln(P_{MAST}/P_{scal})/\ln(\varepsilon_{MAST}/\bar{\varepsilon}_{scal})\sim0.5$, where $\bar{\varepsilon}_{scal}=(0.15+0.37)/2$ is the centre of ε in the international database. Detailed analysis requires a regression on the whole database including the MAST data and such a study will be presented by the international working group [7].

Energy confinement dataset

To compare meaningfully MAST data with ELMy H-mode energy confinement time scalings the plasmas should be quasi-stationary. In particular, acceptance to the International

ELMy Dataset requires that the time-derivative of energy content dW/dt is small:

$$-0.05 \leq (dW/dt) / P \leq 0.35 \quad (1)$$

where P is the absorbed power. Also the duration of such a regime should be sufficiently long in comparison with the energy confinement time. To satisfy the criterion (1) the MAST data have been critically extracted from dedicated discharges. The data consist of plasmas with a double null divertor configuration with deuterium as a working gas. Neutral beam injectors use both hydrogen and deuterium. In engineering parameters the dataset covers the range: I_p=0.64-0.87MA, B_T=0.38-0.49T, R=0.75-0.87m, a=0.55-0.58m, line average density n=(3.2-4.2)$\times 10^{19}$m^{-3}, κ=1.8-1.95 and power loss P_L= 1.5-2.4 MW. An example discharge is shown in fig. 2. The energy content is determined from equilibrium reconstruction (EFIT). When this is compared with the kinetic measurement using temperature and density profiles (see fig.3) good agreement is obtained showing that the contribution from fast ions is small. For the injected energy of neutral beams (40keV) and the plasma density range specified above, shine-through losses are negligible and we assume that all the beam energy is dissipated in the plasma. On the other hand the data have been restricted to lower densities to avoid poor beam penetration. For this density range it is calculated that about 73-80% of the beam is deposited inside 2/3 of the minor radius. The dataset consists of time slices with and without sawteeth. The shots with sawteeth can suffer from the presence of neoclassical tearing modes (NTM). The data represent quasi-stationary ELMy plasmas, however the ELM are irregular. In particular, the increase of ELM frequency with increasing power, a typical characteristic of type-I ELMs, has not yet been observed.

Fig. 4 shows the MAST data compared with the IPB98(y,2) scaling. The range of energy confinement time τ_E is related to its proportionality to the plasma current. The dependence on power and density is undetermined in MAST dataset, partially due to the correlation between n and P_L. In addition, the power dependence of confinement time is affected by the observed decrease of ELM frequency when the power is increased. The data are distributed close to the prediction of the scaling and thus, in the first order approximation, the MAST data confirm the aspect ratio dependence in the IPB98(y,2) scaling.

To quantify more detailed effects the MAST data have been merged with the published International Confinement Database [8]. The aspect ratio scaling is expected to be most strongly influenced by the data from the smallest and largest aspect ratio tokamaks in the dataset, MAST and PBX-M respectively. Table 1 shows the exponent of the inverse aspect ratio x_ε in the power law scaling derived from log-linear regression. The first line is a repeat of the regression on the dataset from which the IPB98(y,2) scaling is derived. The second line corresponds to the "medium aspect ratio dataset" (IPB98(y,2) dataset without PBX-M). The third line shows the effect of adding MAST to the "medium aspect ratio dataset". Firstly, it is seen that MAST data make the database more symmetric around the ITER point (ε_{ITER}=0.32) and thus strengthen the database predictive capability. Secondly, adding MAST data to the "medium aspect ratio" dataset results in a smaller change of the scaling and lower RMSE than adding PBX-M. This could be the residual of re-normalisation of elongation in order to accommodate the "bean" shape cross-section of PBX-M. In this sense the MAST data form a homogeneous dataset with the tokamaks of conventional cross-section and support a somewhat stronger aspect ratio dependence than given by the IPB98(y,2) scaling.

Table 1. Effect of MAST data on the aspect ratio exponent in the power law scaling $\tau_E \propto I^{xI} B^{xB} n^{xn} P^{xP} M^{xM} R^{xR} \varepsilon^{x\varepsilon} \kappa_a^{x\kappa}$ [8]. The Kadomtsev constraint is used. MAST data are weighted stronger to balance larger number of PBX-M data points.

	εmin	<ε>	εmax	x_ε	N	RMSE %
IPB98y2	0.15	0.29	0.40	**0.57±0.04**	1310	14.5
IPB98y2-PBXM	0.20	0.29	0.40	**0.79±0.05**	1251	14.2
IPB98y2-PBXM +MAST(w=4)	0.20	0.31	0.73	**0.80±0.05**	1263	14.4

Alternatively two-term energy confinement scaling, $\tau_E=(W_{core}+W_{ped})/P_L$, is used, where W_{core} and W_{ped} are the core and pedestal energy content respectively. The leading scaling has the form $W_{ped,scal}=e^{-3.7} I^{1.7} R^{1.16} P^{0.31} M^{0.30} q_{sh}^{1.2}$, where $q_{sh}=q_{95}/q_{cyl}$ [9]. This scaling is derived from the subset of "medium aspect ratio" tokamaks with a small range of ε=0.24-0.37 [10]. Therefore the scaling has no aspect ratio dependence and thus MAST data are expected to provide a powerful constraint. Figure 5 shows the evaluation of the electron pedestal energy content, for a quasi-stationary ELMy H-mode discharge, from Thomson scattering measurements (300 spatial points). The pedestal position in poloidal flux co-ordinates is determined as $\psi_{N,ped}= \psi_0-2.5\Delta$, where the pedestal width Δ and pedestal edge ψ_0 are determined from the fitting of a function $a\times\tanh((\psi_N-\psi_0)/\Delta)+b$ to the density profile at the inboard mid-plane. The measured value $W_{e,ped}$=6.8kJ is more than 4-times lower than predicted by the scaling: $0.5\times W_{ped,scal}$=30kJ. This means that MAST data would introduce about a quadratic aspect ratio dependence in the pedestal scaling $W_{ped,scal}\propto\varepsilon^{-2}$.

Conclusions

Data-sets of power threshold and energy confinement of ELMy H-mode from the low aspect ratio tokamak MAST have been assembled. Comparisons with international scalings show that: (1) MAST introduces a weak positive ε-dependence in the L-H power threshold. (2) The data are consistent with the IPB98(y,2) scaling but support a somewhat stronger aspect ratio dependence consistent with tokamaks with conventional cross section. (3) MAST indicates a quadratic *R/a*-dependence for pedestal energy scaling.

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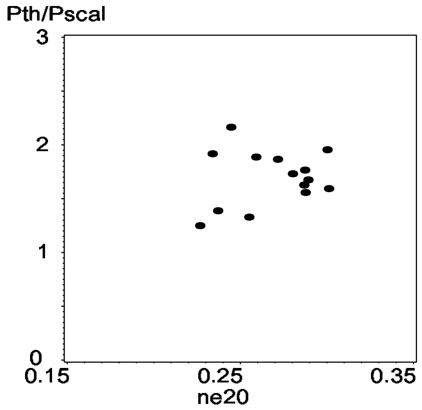

Fig. 1. L-H threshold power P_{th} normalised to the scaling $P_{scal}=0.061n_{20}^{0.53}B_T^{0.78}S^{0.83}$ [6] as function of line averaged density in units of $10^{20}m^{-3}$.

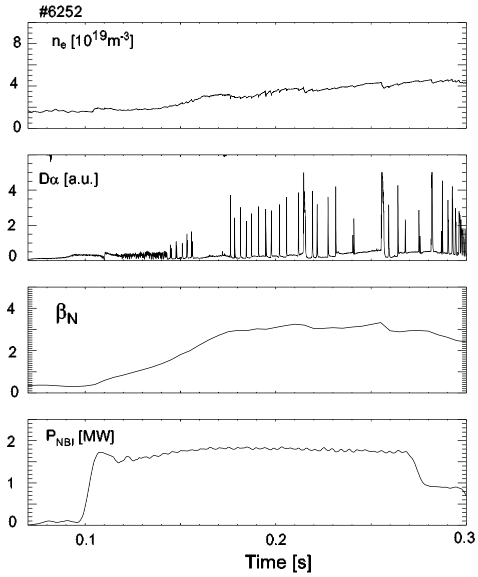

Fig. 2. Quasi-stationary ELMy H-mode. The traces from top to the bottom denote: line-averaged density, D_α emission, normalised beta and neutral beam power. I_p=0.73MA, B_T=0.46T, deuterium plasma, deuterium NBI.

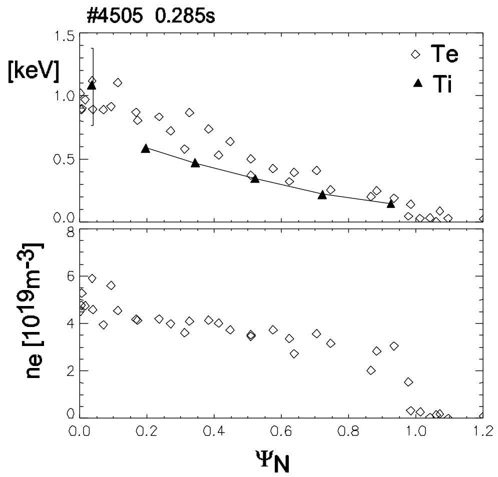

Fig. 3. Profiles of electron (T_e) and ion (T_i) temperature and electron density (n_e) in a quasi-stationary ELMy discharge. T_e, n_e from T.S, T_i from CX and NPA. I_p=0.72MA, B_T=0.43T, P_{NBI}=1.7MW, deuterium plasma, hydrogen NBI. W_{mhd}=73kJ, W_{ekin}=39kJ, ratio of T_i/T_e~0.85.

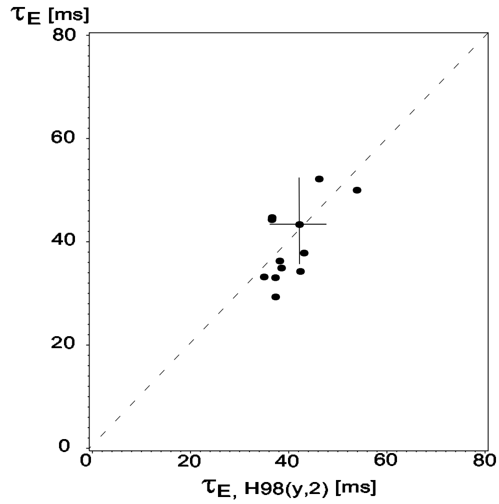

Fig. 4. Energy confinement time in compared with the prediction of the IPB98(y,2) scaling.

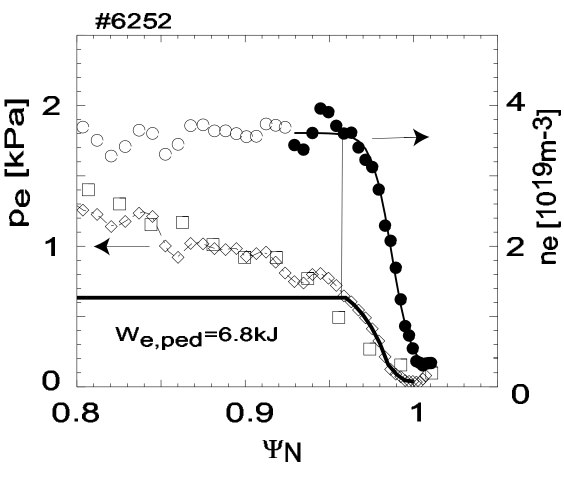

Fig. 5 Evaluation of pedestal electron energy content.