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Testing H-mode parameter similarity in JET and ASDEX Upgrade

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Introduction

Similar plasmas in tokamaks of different size can serve to identify critical parameters for confinement and H-mode operational boundaries. Depending on the choice of similarity parameters, different size scalings for dimensional quantities follow. Fully ionised plasmas described by Maxwell's equations (excluding Poisson's equation) and the Fokker-Planck equation can be characterized by three free parameters [1], for example $\rho*$, $\nu*$, β [2]. If geometry (plasma cross section, aspect ratio safety factor profile) and ion mass are kept identical the following scaling holds for dimensional parameters B (magnetic field components), I_p (plasma current), n (electron, ion density), T (electron, ion temperature) and P (heating power):

$$\omega, B \propto R^{-5/4},\ I_p \propto R^{-1/4},\ n \propto R^{-2},\ T \propto R^{-1/2},\ P \propto R^{-3/4} \tag{1}$$

At the plasma edge the interaction with neutral particles may become important, in which case the absolute temperature T is a similarity parameter because of the energy dependence of atomic cross sections [3, 4]. In general, there is no similarity of plasmas of different size because only three free engineering parameters (B_t, n or gas rate, and P) are available to match ρ^*, β, ν^* and T. However, similarity is possible if one of these parameters can be neglected. This can be tested in separate similarity experiments with corresponding size scalings:

$$\omega, B \propto R^{-1/2},\ I_p \propto R^{1/2},\ n \propto R^{-1},\ P \propto R^{1} \quad (\nu^*, \beta, T) \tag{2}$$
$$\omega, B \propto R^{-1},\ I_p \propto R^{0},\ n \propto R^{-2},\ P \propto R^{0} \quad (\rho^*, \beta, T) \tag{3}$$
$$\omega, B \propto R^{-1},\ I_p \propto R^{0},\ n \propto R^{-1},\ P \propto R^{1} \quad (\rho^*, \nu^*, T) \tag{4}$$

Previous comparison of JET and ASDEX Upgrade has shown a match of $\rho*$, ν^* and β core profiles in H-mode and at the plasma edge at the time of the L-H transition [5]. This experiment has now been repeated with improved shape match, closed divertor in both machines, and neutral beam voltage upgraded in ASDEX Upgrade to allow more central and better matching heat deposition. In addition and for the first time, tests of $T = const$ similarity models according to Eqs. 2 - 4 for the L-H transition are presented.

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[1] see appendix of J. Pamela, "Overview of recent JET results", proceedings of IAEA conference on Fusion Energy, Sorrento 2000

Matching parameters	Exp.	shot	I_p (MA)	B_t (T)	$\overline{n}_e^\dagger$ $10^{19}\mathrm{m}^{-3}$	P_{NBI} (MW)
ρ^*, ν^*, β (core)	AUG	15923	1.2	2.4	7.2	6.2
	JET	53856	1.0	1.2	2.4	3.7
ρ^*, ν^*, β (edge, L-H)	AUG*	10050	1.2	3.0	3.4	$3.0^\ddagger$
	JET*	43904	1.2	1.8	1.24	$3.0^\ddagger$
	AUG	13927	1.2	3.0	4.26	$4.0^\ddagger$
	JET	52378	1.0	1.4	1.26	$2.2^\ddagger$
ν^*, β, T (edge, L-H)	AUG	13927	1.2	3.0	4.26	$4^\ddagger$
	JET	50733	1.6	2.2	2.35	$2.6^\ddagger$
ρ^*, β, T (edge, L-H)	AUG	13930	1.2	3.0	5.96	$4.3^\ddagger$
	JET	50726	1.2	1.7	1.78	$1.7^\ddagger$
ρ^*, ν^*, T (edge, L-H)	AUG	13927	1.2	3.0	4.26	$4^\ddagger$
	JET	50727	1.2	1.7	2.12	$2.0^\ddagger$

Table 1: Parameters of best matching discharges in JET and ASDEX Upgrade for core profile and edge similarity.

† central line averaged density for core, peripheral sightline for edge similarity experiments.
‡ threshold power
⋆ data from Ref. [5]

Experiments

Neutral beam-heated deuterium plasmas in lower single configuration (favourable ion-grad$B$ direction) are made in JET (major radius of geometrical center $R_{geo} = 2.95$ m) and ASDEX Upgrade (AUG, $R_{geo} = 1.65$ m). The scaled cross sections of closed flux surfaces (low β_p case at L-H transition) is shown in Fig. 1. The aspect ratio $A \approx 3.3$ is approximately matched. The nominal separatrix positions at midplane from equilibrium reconstruction are $R = 2.155$ m (AUG) and $R = 3.82$ m (JET). Profiles of electron density, electron and ion temperature are obtained from LIDAR (JET), Thomson scattering measurements (AUG), Li-beam (AUG), ECE radiometry (JET and AUG) and charge exchange spectroscopy (JET and AUG). For each model test, the values of B_t and I_p and n_e are set according to Eqs. 1-4. For the edge comparison, a peripheral interferometer chord (V4 at JET) is compared against the equivalent line average calculated from edge density profiles in AUG. Parameters of the best matching shot pairs are listed in table 1. The edge safety factor is $q_{95} = 3.3$ for the core and $q_{95} = 4.1$ for the edge comparison pulses.

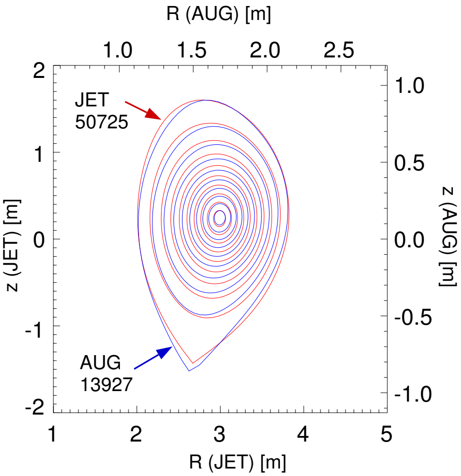

Figure 1: *Cross sections of closed flux surfaces in JET and ASDEX Upgrade.*

Core profiles

For a test of H-mode core profile match, matching neutral beam heating power is set (first case in Table 1). In ASDEX Upgrade, the voltage of 2 out of 3 beam sources is adapted to achieve a roughly similar heating profile. In both machines, type I ELMy H-mode is obtained for these parameters. A fair match of scaled density profiles and a very good match of electron and ion temperature profiles within error bars are obtained (Fig. 2). With engineering parameters set according to Eq. 1 similarity of full density and temperature profiles indicate that profiles of ρ^*, ν^*, and β are matching.

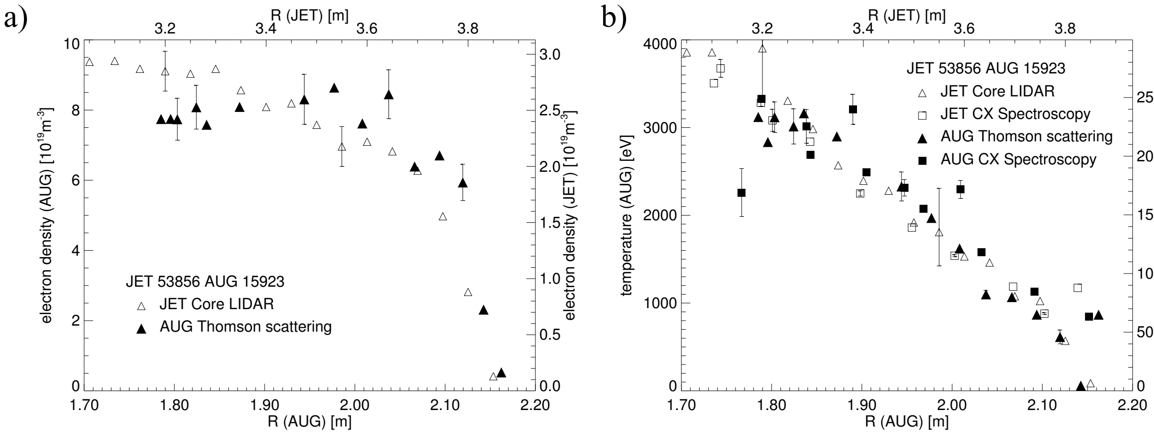

Figure 2: *Core electron density profiles(a), ion and electron temperature profiles (b) in JET and ASDEX Upgrade matching H-mode plasmas, scaled according to Eq. 1*

L-H transition

Similarity of edge parameters is tested for the H-mode threshold. L-mode plasmas are produced in both machines with matching B_t, I_p and edge line averaged density $\overline{n}_e$ for each model (Eqs. 1-4). The neutral beam power is ramped up slowly across the H-mode transition by switching one beam source with varying duty cycle. The edge temperatures are measured just

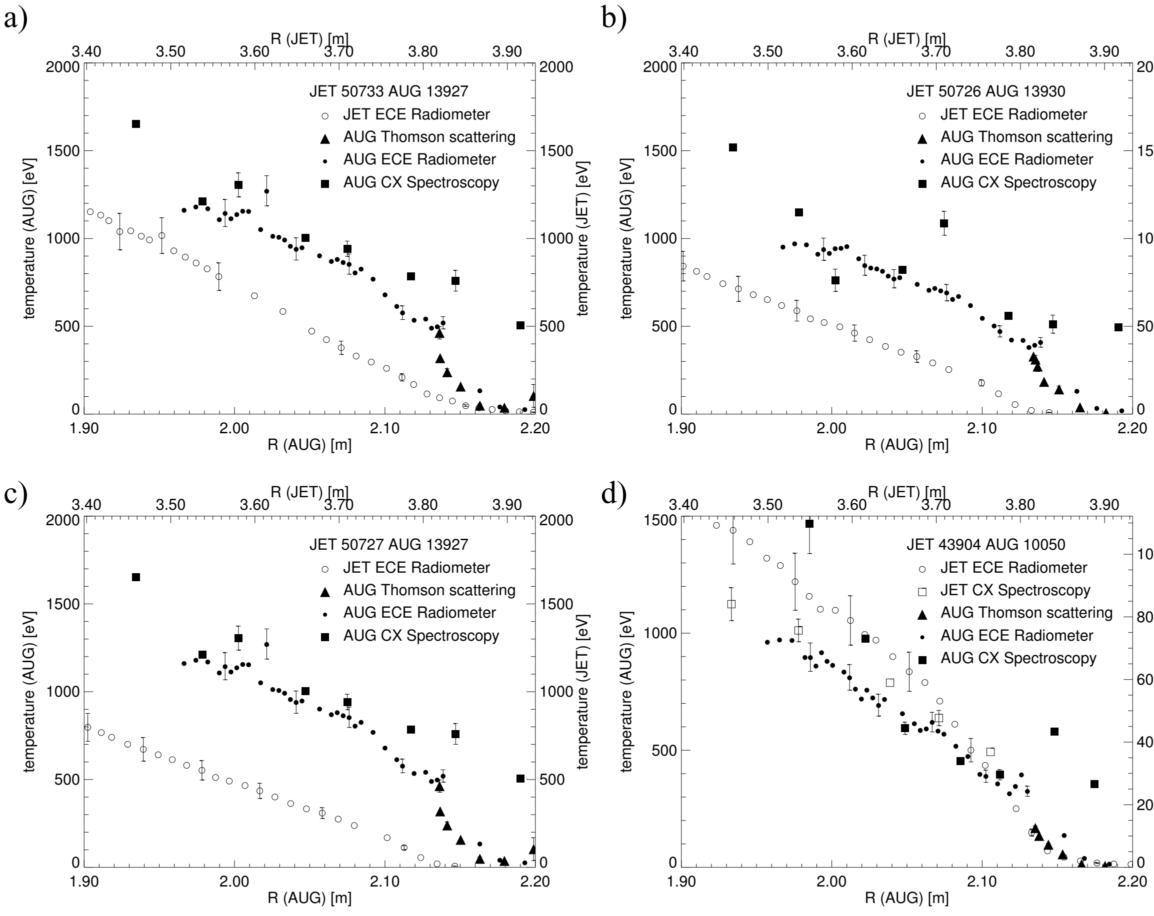

Figure 3: *Edge electron and ion temperatures at the plasma edge just before the L-H transition in JET and ASDEX Upgrade testing different similarity parameter sets (Eq. 1-4) (a)* β, $\nu*$, *T, (b)* β, ρ^*, *T, (c)* ν^*, ρ^*, *T. Only similarity of* ρ^*, β, ν^* *(d, from Ref.[5]) is compatible with the edge data.*

before the L-H transition. A match of scaled T implies a match of all similarity parameters.

Electron temperature profiles are shown in Fig. 3 for the four experimental tests. For the ρ^*, β, ν^* test (Fig. 3 d) we quote the result of Ref. [5] because of the availability of edge ECE measurements in both machines. For AUG, also T_i is shown, which is roughly equal to T_e inside the separatrix.

With parameters set to test $T = const.$ models (Eqs. 2-4) the temperatures in JET and ASDEX Upgrade differ significantly at all radii (Fig. 3 a-c) while for the ρ^*, ν^*, β test the scaled temperatures near the separatrix are in agreement (Fig. 3 d, Ref. [5]). The threshold power (Table 1) is lower in JET than in AUG in all cases as predicted only for identity of ρ^*, ν^*, β (Eq. 1). We conclude that the experimental data supports ρ^*, ν^*, β as critical parameters and contradicts the $T = const$ models.

Summary and conclusions

Matching plasmas have been made in JET and ASDEX Upgrade with identical profiles of ρ^*, ν^* and β in H-mode in the plasma core and at the plasma edge at the time of L-H transition. Although this result has been obtained for a matching set of parameters and therefore does not provide a scaling, it supports (once more) the application of dimensional constraints for H-mode confinement and threshold scalings.

For the first time, it has been tested experimentally whether the absolute edge temperature T at the plasma edge is a critical parameter for the H-mode transition. With engineering parameters set to match T and any combination of two quantities out of ρ^*, ν^* and β, no match could be obtained. Consequently, T is not a similarity parameter or none of the above parameters can be neglected, in which case no similarity is possible in plasmas of different size. Previous scalings of the local edge threshold condition in ASDEX Upgrade [6] and the International H-mode threshold data base [7] are close to expressions in dimensionless parameters (ρ^*, ν^*, β) which indicate a weak dependence on ν^*. If ν^* is not a critical parameter for the transition, the failure of the (β, ρ^*, T) similarity test indicates that T is not a similarity parameter.

Consequently, it is unlikely that atomic physics processes dominate the H-mode threshold scaling at the parameters of the present experiment. Upscaling is not straightforward as for fixed (ρ^*, ν^*, β), $n \times R \propto R^{-1}$ and $T \propto R^{-1/2}$ hence the transparency of the scrape-off-layer for recycling neutrals to reach the velocity shear region near the plasma boundary increases with plasma size. However, for ITER FEAT parameters ($R = 6.2$ m, $I_p = 15$ MA), assuming $n_{\mathrm{LH}} = 0.5\, n_{\mathrm{GW}}$, $n \times R$ is larger than for JET or AUG. In addition, from Ref. [7] a significantly larger critical edge temperature for the transition is expected so that the scrape-off layer is even more opaque than in the present experiments.

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