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W. Suttrop, L.D. Horton, A.E. Hubbard, D. McDonald, R. Barnsley, M. Beurskens, P. Bonoli, J.-M. Chareau, J.G. Cordey, J.W. Hughes, P.J. Lomas, G. Maddison, A. Meigs, F. Meo, D. Mossessian, R. Neu, J.-M. Noterdaeme, V.V. Parail, F. Ryter, J. Schweinzer, M. Stamp, J.D. Strachan, J. Stober and S. Wukitch

Parameter Similarity Studies in JET, ASDEX Upgrade and ALCATOR C-Mod

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W. Suttrop[1], L.D. Horton[1], A.E. Hubbard[2], D. McDonald[3], R. Barnsley[3], M. Beurskens[3], P. Bonoli[2], J.-M. Chareau[5], J.G. Cordey[3], J.W. Hughes[2], P.J. Lomas[3], G. Maddison[3], A. Meigs[3], F. Meo[1], D. Mossessian[2], R. Neu[1], J.-M. Noterdaeme[1], V.V. Parail[3], F. Ryter[1], J. Schweinzer[1], M. Stamp[3], J.D. Strachan[6], J. Stober[1], S. Wukitch[2],
and ASDEX Upgrade Team, ALCATOR C-Mod
and contributors to the EFDA-JET workprogramme*

[1]Max-Planck-Institut für Plasmaphysik, EURATOM Association, Garching, Germany
[2]Plasma Science and Fusion Center, M.I.T., Cambridge, Mass., U.S.A.
[3]UKAEA Fusion, Culham Laboratory, Euratom Association, Abingdon, U.K.
[4]FOM Instituut voor Plasmafysica "Rijnhuizen", EURATOM Association, Trilateral Euregio Cluster, Nieuwegein, The Netherlands
[5]Association EURATOM/CEA Cadarache, DRFC, Saint-Paul-Lez-Durance, France
[6]Princeton Plasma Physics Laboratory, Princeton University, New Jersey, U.S.A
** See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

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ABSTRACT.

Dimensionally similar discharges are investigated in ASDEX Upgrade, JET and ALCATOR C-Mod to study critical parameters for the H-mode transition and the boundary of the "Enhanced D-Alpha" (EDA) H-mode regime. Comparison of JET and ASDEX Upgrade confirms that the H-mode transition can be obtained at same values of ρ^*, ν^*, β at the edge and rules out the absolute temperature T as a similarity parameter. Attempts to reproduce the EDA regime of ALCATOR C-Mod in ASDEX Upgrade have not been successful. The matching pedestal collisionality is found inaccessible due to H L back-transition. Possible reasons for the mismatch of the H-mode boundary are discussed.

1. INTRODUCTION

Variation of the size of magnetically confined fusion plasmas helps to identify critical dimensionless parameters for transport, plasma stability and regime boundaries. A fully ionized magnetized plasma can be characterized by a set of three dimensionless parameters, normalized gyroradius ρ^*, collisionality ν^*, and plasma pressure β [1, 2]. At the plasma edge, atomic processes such as interaction with neutral particles may become important, introducing the absolute temperature T as a fourth similarity parameter [3]. For similarity experiments in tokamaks with fixed geometry, typically only three free parameters are available (magnetic field B_t , plasma density n_e and heating power P_{heat}) so that in the most general case, dimensionless identical plasmas at different size need not exist. However, if one parameter is irrelevant, similarity of the remaining three parameters should recover the same physics effects (e.g. regime transitions). The size scalings of engineering parameters for the four combinations of three out of four parameters ρ^*, ν^*, β, T are:

$$T \propto R^{-1/2},\ \omega,\ B \propto R^{-5/4},\ I_p \propto R^{-1/4},\ n \propto R^{-2},\ P \propto R^{-3/4} \qquad (\rho^*, \nu^*, \beta) \qquad (1)$$

$$\omega,\ B \propto R^{-1/2},\ I_p \propto R^{-1/2},\ n \propto R^{-1},\ P \propto R^{1} \qquad (\nu^*, \beta, T) \qquad (2)$$

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

$$\omega,\ B \propto R^{-1},\ I_p \propto R^{0},\ n \propto R^{-1},\ P \propto R^{1} \qquad (\rho^*, \nu^*, T) \qquad (4)$$

While typically dimensional constraints are applied to core confinement studies (e.g. [4]) we report here recent experiments to test similarity of local edge parameters for operational 2 regime boundaries, (a) similarity of H-mode threshold edge parameters in JET (major radius R_{geo} 2.95m) and ASDEX Upgrade (R_{geo} = 1.65 m) and (b) conditions for the "Enhanced D-alpha" (EDA) regime [5] and H-mode threshold in similar plasmas in ALCATOR C-Mod (R_{geo} = 0.68m) and ASDEX Upgrade.

2. JET - ASDEX UPGRADE SIMILARITY EXPERIMENTS

A series of similarity experiments has been carried out in JET and ASDEX Upgrade to test similarity of ρ^*, ν^*, β for H-mode core profiles [6], local edge parameters at the H-mode transition [7], and, most recently, T const constraints for the L-H transition [8]. For these experiments, neutral beam-heated deuterium plasmas in lower single null configuration (favorable ion-grad B direction) with matching plasma shape and approximately matching aspect ratio (A = 3.3) are studied in JET and ASDEX Upgrade.

For core profile comparison, the neutral beam acceleration voltage is adjusted in ASDEX Upgrade to produce a similar beam power deposition profile in both experiments. A fair match of scaled density profiles and a very good match of electron and ion temperature profiles within error bars are obtained. The similarity of density and temperature profiles over the entire plasma radius indicates that profiles of ρ^*, ν^*, β are matching, confirming the previous results [6].

Similarity of edge parameters is tested for the H-mode threshold in JET and ASDEX Upgrade. Separate pairs of discharges are produced for each combination of three out of the four candidate parameters ρ^*, β, ν^* and T . The L-mode target density match is based on an edge interferometer chord (V4) at JET, which is compared against the equivalent line average calculated from edge density profiles in ASDEX Upgrade obtained by common deconvolution of lithium beam and interferometer measurements. The neutral beam power is ramped up slowly across the H-mode transition by switching one beam source with varying duty cycle and heating power and edge temperatures are measured just before the L-H transition. A match of scaled T implies a match of all similarity parameters.

Electron temperature profiles are shown in Fig. 1 for the four experimental tests. With pa-rameters set to test T = const models (Eqs. 2-4) the temperatures in JET and ASDEX Upgrade differ significantly at all radii (Fig. 1 a-c) while for the ρ^*, ν^*, β test the scaled temperatures near the separatrix are in agreement (Fig. 1 d, Ref. [7]). The threshold power is lower in JET than in ASDEX Upgrade 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.

3. ALCATOR C-MOD - ASDEX UPGRADE SIMILARITY EXPERIMENTS

In a second series of experiments, critical access parameters are compared for the “Enhanced D-alpha” (EDA) regime of ALCATOR C-Mod [5] and type II ELMy H-mode as found in ASDEX Upgrade [9] in dimensionally similar discharges. Two different configurations are used:

i) a configuration with small distance of the secondary and active separatrix ($\delta_l = 0.39$, $\delta_u = 0.28$, $\kappa = 1.58$, “type II ELM” shape), which is found crucial to obtain type II ELMs in ASDEX Upgrade [9]

ii) A high triangularity ALCATOR C-Mod EDA-mode plasma ($\delta_l = 0.47$, $\delta_u = 0.3$, $\kappa = 1.57$, “EDA-shape”).

For both types of plasmas the hydrogen minority is heated with matching power and approximately matching RF frequency, 30 MHz in ASDEX Upgrade and 70 or 80 MHz in ALCATOR C-Mod.

In the closest matching pulse pair in “type II ELM” shape, ELM-free H-mode with contin-uously increasing plasma density and radiation is obtained in both machines with very similar characteristics: Matching time scales, back-transition induced by impurity accumulation and matching electron density and electron temperature profiles at matching time after the transition to ELM-free H-mode. Compared with type II ELMy plasmas in ASDEX Upgrade this configuration is run at about 30% lower normalized density to match the C-Mod plasma conditions which are obtained with the maximum heating power in C-Mod at this shape (3.8MW). Actual type II ELMy plasmas are obtained in ASDEX Upgrade at higher density ($\geq 80\% \times n_{GW}$) and at higher heating power (5MW), significantly above the matching power (2MW).

First attempts are targeted to reproduce the "EDA" regime of ALCATOR C-Mod in dimensionally similar plasmas in ASDEX Upgrade. The target discharges in ALCATOR C-Mod were at $I_p = 0.9$ MA, $B_t = 5.2$T, $P_{ICRH} = 3.6$MW and at $I_p = 1.0$ MA, $B_t = 5.4$T $P_{ICRH} = 3.4$MA, both in EDA mode. ASDEX Upgrade plasmas with heating power, magnetic field and plasma density scaled for matching ρ , β and ν showed ELMy H-mode behavior, with slow type I ELMs. Figure 2 shows edge electron density and temperature profiles (Thomson scattering) for the best matching discharge pair. In ASDEX Upgrade, edge Thomson scattering measurements with high resolution in the edge gradient region are not available for this plasma shape with matching aspect ratio. A match of edge density andtemperature on the pedestal top within 10−15% is ob-tained, with edge temperatures in ASDEX Upgrade being slightly larger than the scaled ALCATOR C-Mod target. The pedestal top parameters correspond to aan electron collisionality of 2.1 for ALCATOR C-Mod and 1.4 for ASDEX Upgrade, assuming the same val-ues of $Z_{eff} = 2$ in both machines. Two different techniques have been attempted to reduce the edge temperature in ASDEX Upgrade to obtain a better match. A reduction of heating power leads to a back-transition to L-mode without transition through a stationary ELM-free H-mode phase. When the density is raised from 60% to 80% of the Greenwald density, a higher recycling level and type III ELMs are observed. The ASDEX Upgrade discharges most similar to EDA mode parameters show, in addition to slow type I ELMs, the appearance of coherent edge MHD activity, which appears in between ELMs and disappears before the maximum edge density before an ELM is reached. The mode frequency is centered near 30kHz, corresponding to 80kHz when scaled to ALCATOR C-Mod parameters. The narrow spectrum is reminiscent of that of the "Quasi-coherent mode" [10], observed in the vicinity of 100−40kHz.

Dedicated pulse pairs have been made to test similarity of the H-mode threshold condition. The forward transition to H-mode is probed with a slow ICRH power ramp and matched B_t, I_p and target line averaged density. The power threshold in ASDEX Upgrade (coupled ICRH power at the transition) is found to be 1.6MW, significantly above the scaled threshold power of 1.0MW in the similar ALCATOR C-Mod plasma. Figure 3 shows edge electron temperature profiles just before the transition, scaled to ASDEX Upgrade parameters. The edge temperature in ASDEX Upgrade is significantly higher than the scaled ALCATOR C-Mod values. This experiment has been repeated with the same plasma parameters but NBI heating and resulted in similarly high threshold power. It is interesting to compare the measured threshold parameters with inter-machine scalings, which predict a power threshold in the vicinity of 1−1.2 MW for the present ASDEX Upgrade parameters, depending on the scaling expression used [11, 12], and a critical edge temperature at 90% flux of

200eV for ASDEX Upgrade and 240eV for ALCATOR C-Mod [11]. The actual power threshold in the current experiment appears to be higher in ASDEX Upgrade while the critical temperature is lower in ALCATOR C-Mod.

4. SUMMARY AND DISCUSSION

Core profile similarity experiments in ASDEX Upgrade and JET (type I ELMy H-mode) as well as ASDEX Upgrade and ALCATOR C-Mod (ELM-free H-mode) demonstrate a good profile match, confirming once more the validity of dimensional constraints for confinement scalings. Attempts to reproduce "Enhanced D-alpha" (EDA) mode of ALCATOR C-Mod in dimensionally identical plasmas in ASDEX Upgrade have not been successful so far. This might be due to a mismatch of scaled pedestal temperature (Fig. 2) which in ASDEX Upgrade remains above typical EDA values [13] and cannot be reduced without H-L back-transition. Nevertheless, in closest matching pulses continuous narrow-band MHD activity is observed in between ELMs, similar to the Quasi-coherent mode in ALCATOR C-Mod. At present, there are no indications that this mode contributes to particle transport across the H-mode barrier as the rate of change of the edge density in between ELMs is similar in presence or absence of the mode.

Similarity parameters for the H-mode threshold have been studied in JET and ASDEX Upgrade. While ρ^*, ν^*, β at the plasma edge can be made similar at the H-mode transition together with consistent scaling of the threshold power, attempts to obtain the H-mode transition at the same absolute temperature T combined with all three combinations of two parameters out of (ρ^*, ν^*, β) fail. This results indicates that the H-mode transition in the parameter range probed is not dominated by atomic physics processes. In contrast, first H-mode transition studies on ASDEX Upgrade and ALCATOR C-Mod show a mismatch of both the H-mode power threshold and critical edge temperature in plasmas scaled to match ρ^*, ν^*, β. The origin of this discrepancy is not known at present. In ASDEX Upgrade, the JET similarity plasmas have a higher L-mode target edge density ($3.4-4.3 \times 10^{19}$ m^{-3}) and higher threshold power (3−4MW) than the ALCATOR C-Mod similarity plasmas (density: 2.5×10^{19} m^{-3}). If neutrals are well shielded from the region of the H-mode barrier to form in the JET similarity case but can marginally penetrate into the scrape-off region in the ALCATOR C-Mod similarity plasma the threshold mismatch in the latter case could be a result of different importance of neutral particle interaction in ALCATOR C-Mod and ASDEX Upgrade. Note that because for similarity, $n \propto R^{-2}$, the parameter $n \times a$ is smaller in ASDEX Upgrade, i.e. for larger plasma size the scrape-off layer is less opaque to neutrals. This question must be addressed with more specific physics investigations and cannot be resolved with similarity experiments.

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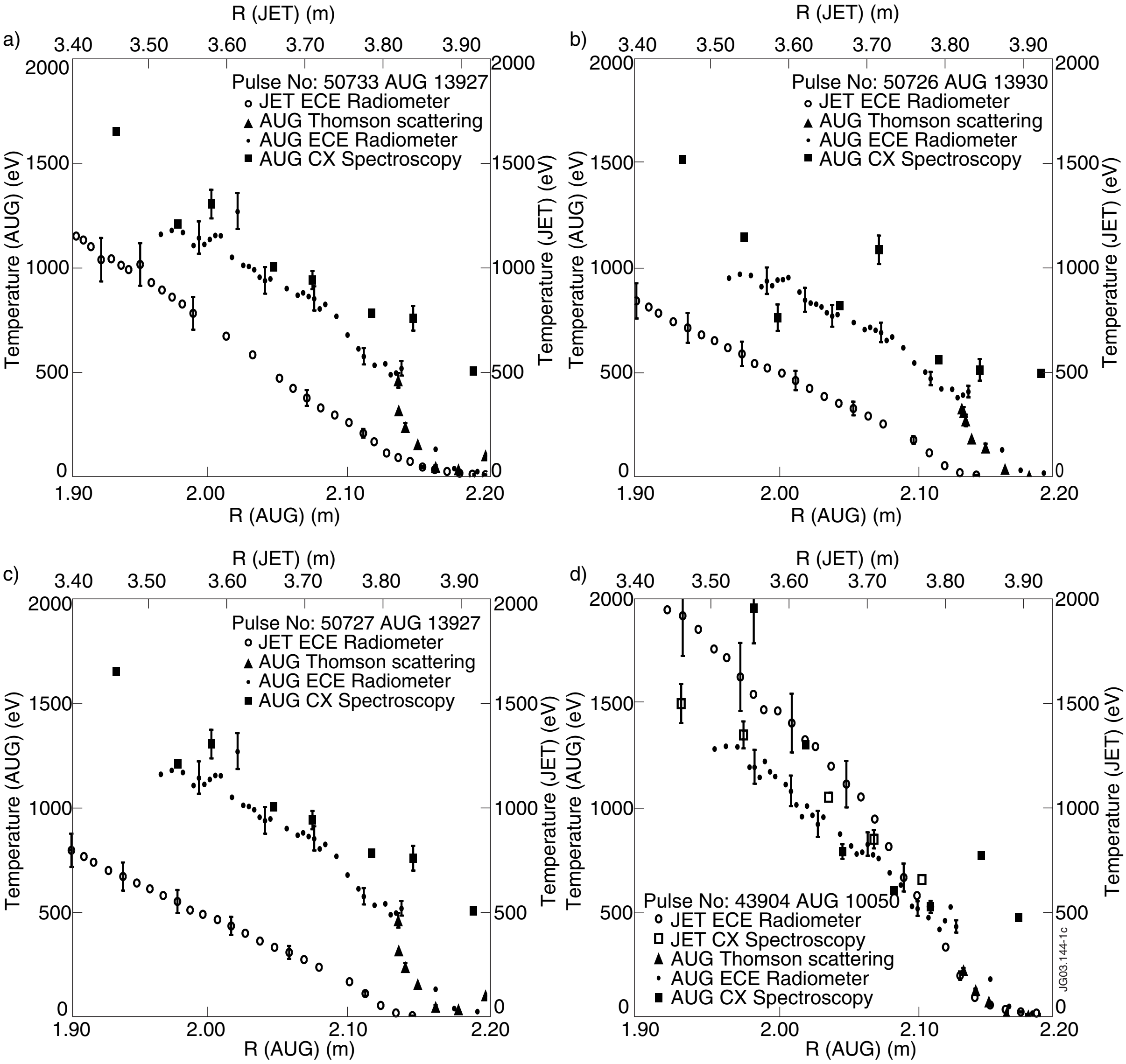

Figure 1: Edge electron and ion temperatures at the plasma edge just before the L-H transition in JET and ASDEX Upgrade testing different similarity parameter sets (Eq. 1-4) (a) β, ν^*, T, (b) β, ρ^*, T, (c) ν^*, ρ^*, T (d) ρ^* , ν^*, β.

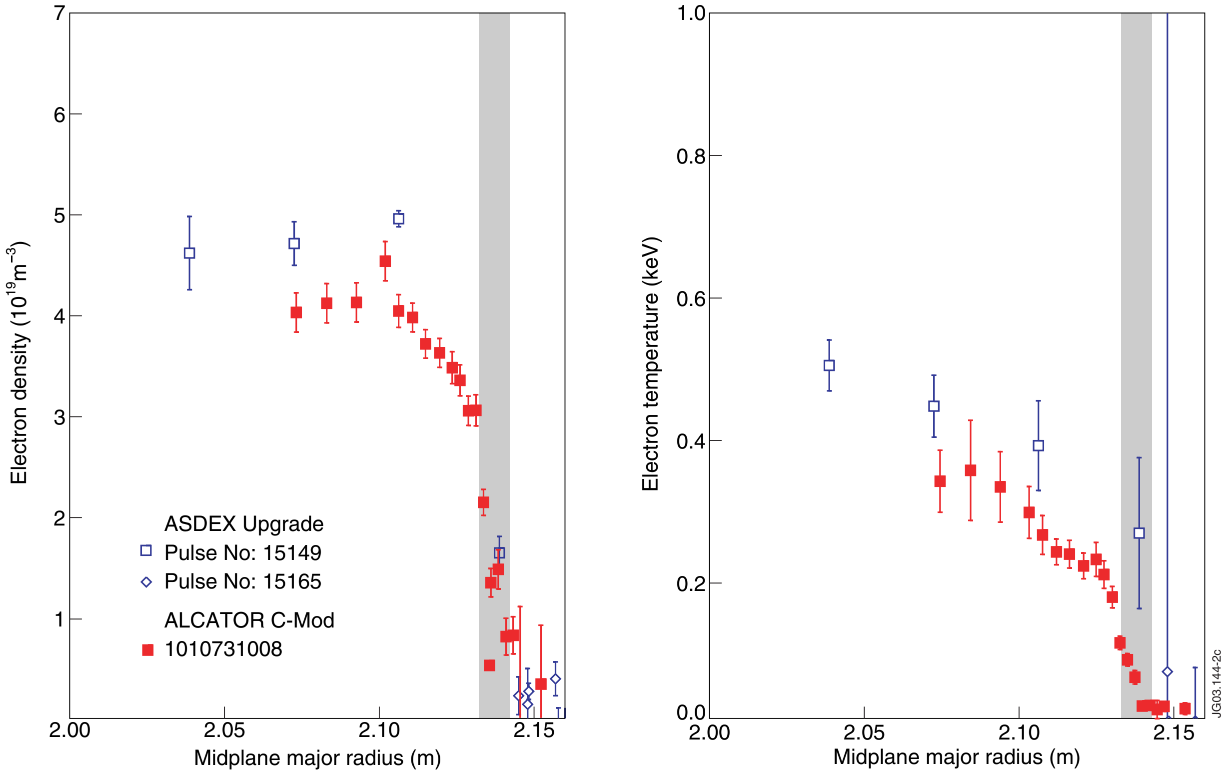

Figure 2: Nearest match of edge profiles of electron temperature and electron density in ASDEX Upgrade (open symbols) and AL-CATOR C-Mod (closed symbols, scaled to ASDEX Upgrade)

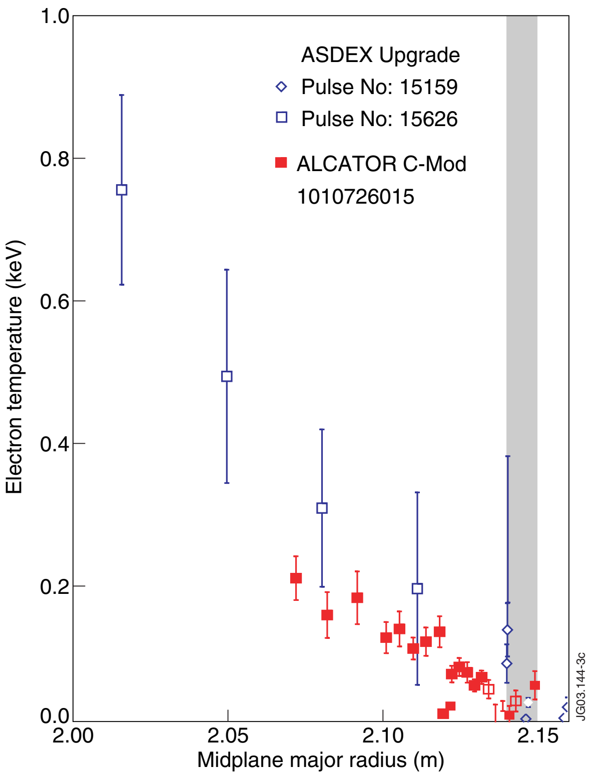

Figure 3: Edge electron temperature profiles in ASDEX Upgrade and AL-CATOR C-Mod (scaled to ASDEX Upgrade) just before the L-H transition