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ABSTRACT

The performance of ELMy H-mode operation in ASDEX Upgrade and JET is compared. Special attention is paid to variations (usually reductions) in this performance near the operational limits which will need to be approached in a next step device. In JET it is found that input powers substantially above the H-mode threshold power are required to obtain discharges with energy confinement enhancement factors at or above the usual ELMy H-mode scalings. Such a margin (as much as a factor of two in JET) is not observed in ASDEX Upgrade. It is proposed that this difference may be due to the higher edge collisionality in ASDEX and the results are compared to a recent theory based on interchange instabilities and magnetic flutter. In ASDEX Upgrade, the confinement in Type I ELMy discharges degrades as the density is raised due to a stiffness of the temperature profiles which leads to a degradation of the core confinement. This type of stiffness is observed in JET only at relatively high edge densities. In JET, the edge confinement degrades as the density is increased by external gas fuelling, consistent with a constant edge pressure gradient and an edge barrier width which reduces in proportion to the edge ion poloidal Larmor radius. In both machines, H-mode performance is limited at high density by a transition first to the Type III ELM regime and then to L-mode. The confinement penalty, relative to good Type I ELM discharges, of operating with Type III ELMs is about 25-30%. The maximum densities for operation with Type I or Type III ELMs can be substantially increased by increasing the plasma triangularity in both machines.

1. INTRODUCTION

The reference operating regime for the next step devices currently being considered by the fusion community is the ELMy H-mode. Unfortunately, the operating point of such a machine will be simultaneously near several boundaries of the ELMy H-mode operating space. In this paper we discuss the influence on plasma performance of operating near these boundaries in JET and ASDEX Upgrade (AUG).

Many, if not all, of the operational limits observed in ELMy H-mode plasmas are controlled by the physics of the plasma in the last few centimeters inside the separatrix. It is thus convenient to describe the limits in a plot of edge temperature versus edge density, the so called edge operation diagram [1,2]. Such a diagram is shown for AUG in Fig.1. Access to the H-mode and to H-mode like plasma performance at low to moderate density and at powers only marginally above the threshold, the lower left corner of Fig.1, will be discussed

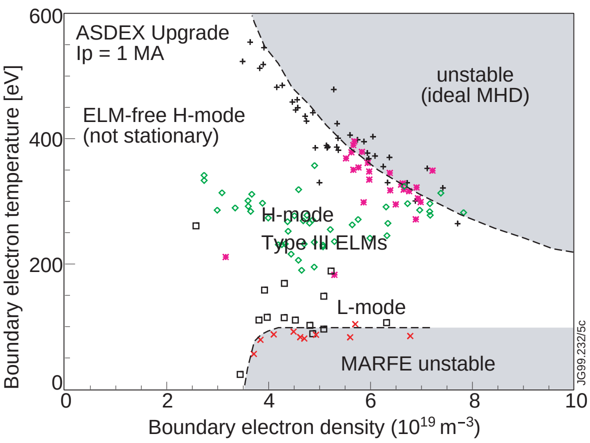

Fig.1: Edge electron temperature versus edge electron density for a variety of ASDEX Upgrade discharges, the so-called edge operation diagram.

in Section 2. Performance of Type I ELMy discharges, along the ideal mhd limit shown in Fig.1, will be discussed in Section 3. Finally, the high density region of the operating space is described in Section 4 and the results are summarised in Section 5.

2. H-MODE THRESHOLD

In JET discharges with input powers only marginally above the H-mode threshold display frequent ELMs and confinement enhancement factors below the usual ELMy H-mode scaling [3]. The frequency of these ELMs decreases with increasing input power and they are thus classified as Type III ELMs [4]. Only when the input power reaches values substantially above the H-mode threshold power do lower frequency Type I ELMs appear and the energy confinement rise to normal ELMy H-mode values ($H_{97} \geq 1$). In Fig.2, the energy confinement enhancement factor is plotted versus input power normalised to the H-mode threshold power [5]. The data are for a series of JET neutral beam heated discharges at 2.5 MA and 2.5 T. In this series of discharges, input powers of more than twice the threshold power were required to obtain steady, Type I ELM discharges. We refer to this power as the Type I ELM threshold power. Note that there is some hysteresis in Fig.2, as indicated by the dashed line. When Type I ELMs are obtained, the particle confinement also improves substantially, the density rises and the calculated H-mode power threshold also rises. Discharges which stay in the Type I ELM regime can thus have normalised input powers somewhat lower, relative to the H-mode threshold, than the highest power Type III ELM discharges [6].

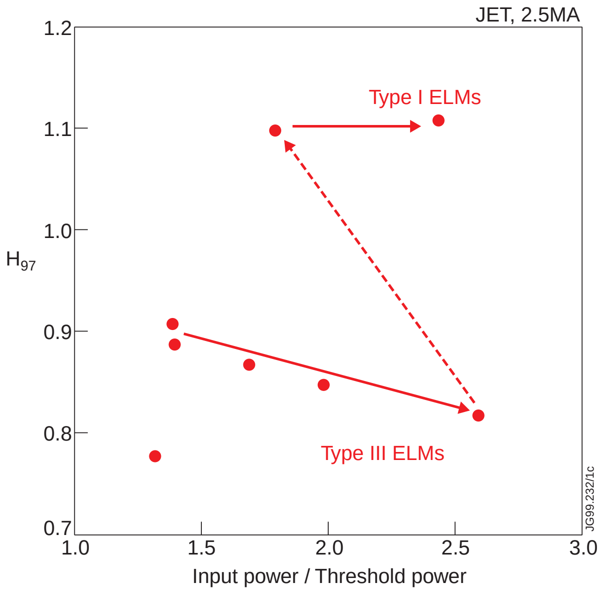

Fig.2: The measured confinement enhancement factor, H97, as a function of input power, normalised to the H-mode threshold power: $P_{LH} = 0.45\, n_{20}^{0.75}\, B\, R^2$. *The data are for a series of neutral beam heated discharges at 2.5 MA and 2.5 T.*

In AUG such a behaviour is not observed. Low to moderate density discharges with input powers above the H-mode threshold evolve spontaneously into the Type I ELM regime. Stationary type III ELMs are only observed in three conditions: with a controlled radiating boundary (the CDH mode [7]); at high edge density; and in hydrogen plasmas.

It may be that the difference in performance between JET and AUG at powers just above the H-mode threshold is related to the difference in edge collisionality of the two machines. The JET data for the H-mode threshold at low density and for operation with Type III ELMs are shown in Fig.3, as well as Type I ELMy discharges for comparison. The threshold data are compared to a theory based on the stabilisation of Alfven drift wave turbulence [8]. The fit coefficients in the theory have been adjusted to match the recent JET data for low density H-mode transitions [9] and are thus not identical to those found in Ref. [8] which were based on AUG data. The Type III ELMy H-mode data have been fit to a recent model for Type III ELMs [10], based on interchange instabilities and magnetic flutter. Again the coefficients for the best fit are somewhat different than those given in the original reference with the JET data requiring a higher critical collisionality. Since there is no edge density profile information available in JET, the edge density shown here is the line averaged density obtained from the outermost chord of the FIR interferometer and it may be that because of this there are systematic data discrepancies between the two machines. The discharges used for investigating the Type I power threshold were performed with little or no external gas fuelling and lie at low to moderate densities (the diamonds in Fig.3). These densities are above the low densities at which the critical temperature for the H-mode transition rises strongly and in the density range where a similar increase in the critical temperature for the Type III to Type I ELM transition is observed. This is the region of the edge operating diagram where there is the largest difference in the two critical temperatures. The AUG Type III ELM data, on the other hand, lie in a region of somewhat higher collisionality (Fig.4) where the difference between the two critical temperatures is smaller. The model results from Ref. [8] and [10] have been overlaid on the data. In the case of AUG, it may be that in this region of operating space the two critical temperatures are sufficiently close so that the improved energy confinement obtained

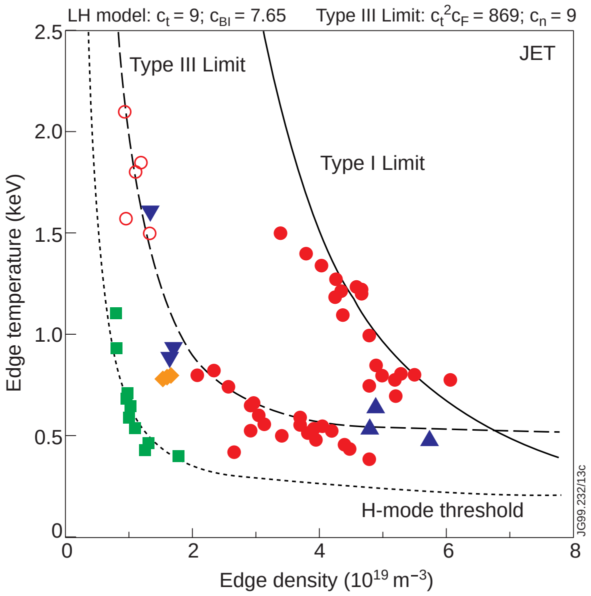

Fig.3: Edge electron temperature versus edge electron density for JET H-mode transitions (squares) and for Type III ELMy discharges (open circles: optimised shear discharges; inverted triangles: discharges following a loss of confinement [6]; diamonds: low power discharges; triangles: discharges with high levels of gas fuelling). The curves are fits to the data based on the theories described in the text. Type I ELMy discharge data are also shown (closed circles), with time points just before and just after the ELM crash included. The upper points, taken just before an ELM follow a curve of $T_e \propto n_e^{-2}$ while the data taken just after the ELM lie on the model fit for Type III ELMs.

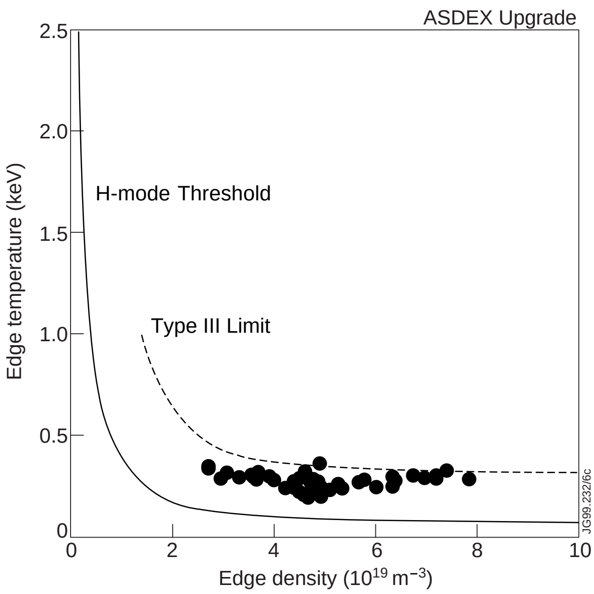

Fig.4: Edge electron temperature versus edge electron density for ASDEX Upgrade Type III ELMy discharges. The curves are fits to AUG data from Ref. [8] for the H-mode transition and from Ref. [10] for the Type III to Type I ELM transition.

after the L-H mode transition is sufficient to increase the edge temperature above the Type I critical temperature and result in a spontaneous evolution into Type I ELMs.

3. TYPE I ELM LIMIT

At sufficiently high input powers, the edge confinement of ELMy H-mode discharges is limited by large amplitude, regular Type I ELM events. In this regime, the pressure gradient in the edge confinement barrier in ASDEX Upgrade is measured to be almost independent of plasma density and only weakly dependent on input power and on edge temperature [2]. The pressure gradient depends primarily on plasma current, increasing as I_p^2 as expected from ideal mhd considerations.

The width of the edge confinement barrier is seen to remain approximately constant as the density is increased. In Fig.5, the product of the edge electron temperature and the edge electron density ($\propto$ edge pressure), measured 2 cm inside the separatrix, is plotted against the fitting function for the edge pressure gradient. For the plasma shapes included in data of Fig.5, the barrier width is measured to be less than 2 cm and the pressure in Fig.5 can thus be used to approximate the electron pressure at the top of the transport barrier. The good correlation implies that the effective width of the barrier, $\Delta = p_{edge} / \nabla p_{barrier}$, remains approximately constant in AUG. A broader scatter of data is observed when the edge pressure is plotted against the product of the pressure gradient and the ion poloidal Larmor radius (see below).

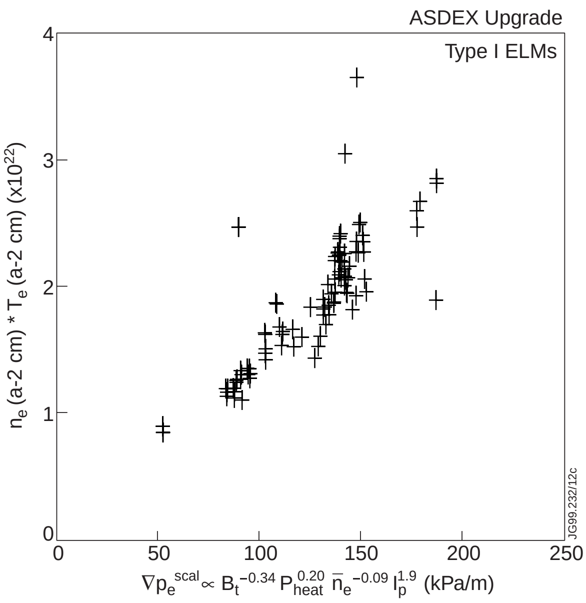

Fig.5: The product of the edge electron density and the edge electron temperature for ASDEX Upgrade plotted against the fitting function for the edge pressure gradient as reported in Ref. [2]. The observed correlation implies that the width of the edge confinement barrier remains constant.

In JET, no measurements of the edge density profile are routinely available and thus there is no information on the edge pressure gradient. It is possible to make estimates of the electron density at the top of the edge barrier using the outermost channel of the FIR interferometer and thus construct an edge pressure. In dedicated series of discharges where the edge density is increased from one pulse to another by increased gas fuelling, it has been shown that the edge pressure in JET scales as $p_{edge} \propto I_p Sh^2 (mT)^{0.5}$, where Sh is the magnetic shear at the 95% flux surface, m is the plasma ion mass and T is the plasma edge temperature ($T_{e,edge} \approx T_{i,edge}$ in JET ELMy H-modes) [11]. This is consistent with a pressure gradient in the edge barrier, $\nabla p_{edge} \propto I_p^2\, Sh^2$, similar to AUG but with an edge barrier width which is proportional to the edge ion poloidal Larmor radius. Such a scaling suggests that ion orbit losses in the plasma edge may be the mechanism for creating a sheared edge electric field which then stabilises the edge turbulence as proposed in the theories of Itoh and Itoh [12] and Shaing and Crume [13]. There is evidence in JET that for neutral beam heated discharges at low density (hot ion H-modes or low density ELMy H-modes) the ion losses from fast injected particles may control the edge barrier width [14,15]. In this case, the scaling $p_{edge} \propto I_p Sh^2 (mE_{fast})^{0.5}$ is found.

The dependence of the edge pressure on the edge temperature implies a degradation of edge confinement as the density is increased by external gas fuelling. This is demonstrated in Fig.6 for three 1.8 MA, 2.4 T, 14 MW JET discharges with varying levels of gas fuelling. As the gas fuelling is increased, the edge temperature drops and the edge density rises in such a way that the edge pressure drops in proportion to $\sqrt{T}$, in contrast to AUG results where the edge pressure and thus the edge confinement remain constant as the density is increased.

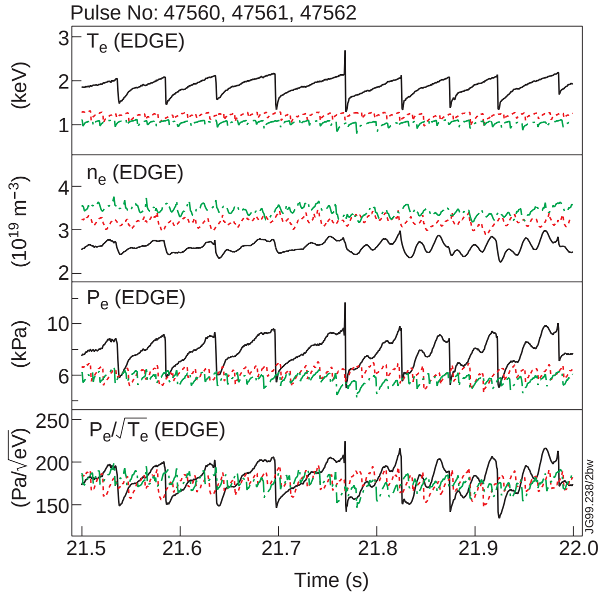

Fig.6: The edge parameters as a function of time during the steady phase of three JET ELMy H-mode discharges. The discharges were all at 1.8 MA, 2.4 T with 14 MW of neutral beam heating and vary only in the amount of additional gas fuelling applied. Pulse 47560 (full curves) was fuelled by the neutral beam injection only, pulse 47561 (short dashed curves) was fuelled with 2.6x10^{22} atoms/s of deuterium gas in addition to the beam fuelling and Pulse 47562 (long dashed curves) with 3.0x10^{22} atoms/s.

In ASDEX Upgrade the global energy confinement also degrades as the density is increased but, in contrast to JET, solely because the core confinement decreases as the edge temperature decreases. In AUG, the profiles of both ion and electron temperature are stiff in the sense that there is a minimum temperature gradient length, $L_T = \left(\frac{1}{T}\frac{dT}{dr}\right)^{-1} = \left(\frac{d(\ln T)}{dr}\right)^{-1}$, which can be achieved and the energy transport adjusts to maintain this scale length [2]. In Fig.7, this profile stiffness is shown for the electron temperature in a variety of AUG discharges with a range of input powers, plasma currents, toroidal fields and densities. The

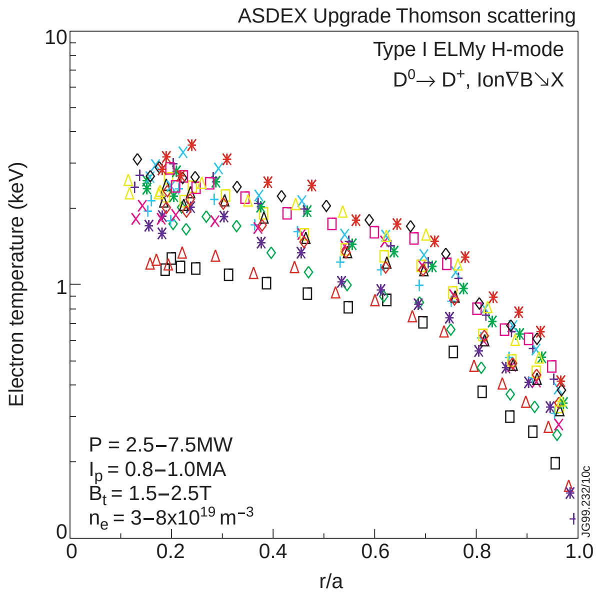

Fig.7: The electron temperature profile, on a log scale, for a variety of ASDEX Upgrade discharge conditions. All pulses are Type I ELMy H-modes.

constant offset of the profiles, in log space, is consistent with a constant temperature gradient length profile as the edge temperature is varied. This type of profile stiffness suggests that ion temperature gradient turbulence may be controlling the transport in AUG plasmas.

In JET, profile stiffness such as that found in AUG is observed only at relatively high gas fuelling rates. The ion temperature profiles of three JET ELMy H-mode discharges are shown in Fig.8. The behaviour of the profiles is typical: at low to moderate gas fuelling rates the edge temperature decreases and the profiles shift downwards on a linear scale (Fig.8(a)) with little change in the core transport; at higher gas fuelling rates the edge temperature continues to drop but the core temperature gradient also reduces so as to keep the core temperature gradient scale length roughly constant (Fig.8(b)). This apparent change in the profile stiffness has been reproduced by a semi-empirical model based on mixed Bohm / gyroBohm transport [16,17]. In this model the Bohm transport is nonlocal and depends on the edge temperature. At low temperatures, the Bohm term increases the transport in the core, reducing the temperature gradient.

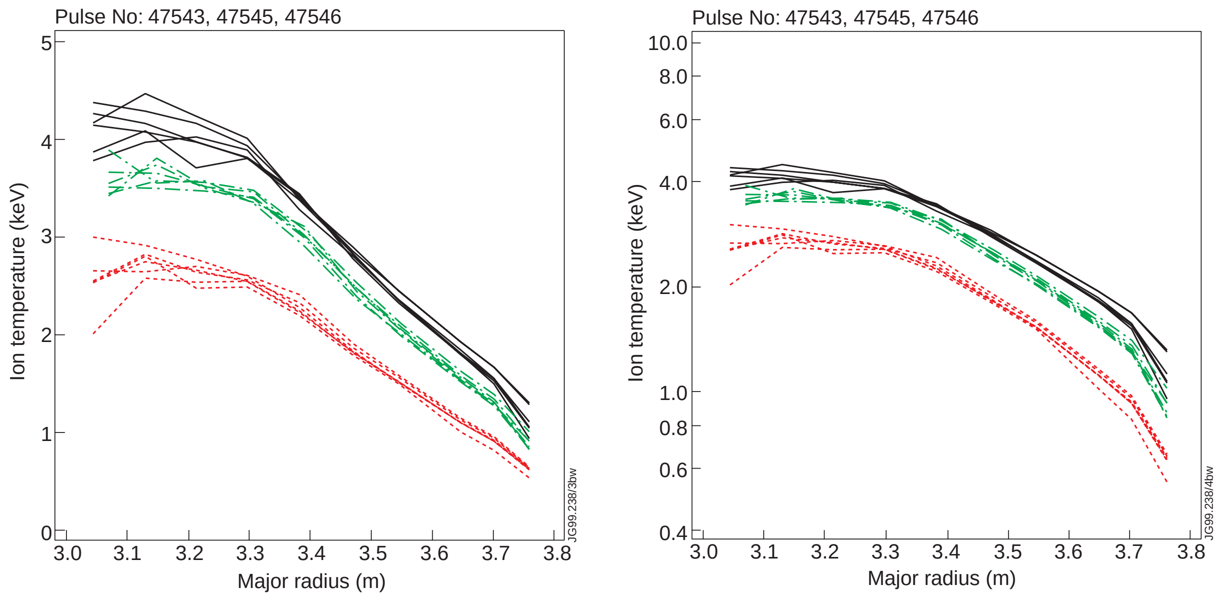

Fig.8: Ion temperature profiles on (a) a linear scale and (b) a log scale for three JET ELMy H-mode discharges with varying levels of gas fuelling.

In order to study profile stiffness, both machines have performed dedicated experiments where the heat deposition profile was substantially varied [18,19]. In the JET experiments the measurements were made in sawtooth-free discharges so as to avoid the complications introduced by the thermal and fast particle transport during sawteeth crashes and, in particular, the influence of different ICRH resonance positions on the sawtooth frequency and amplitude. In the AUG experiment the heat deposition profile was varied by varying the injection energy of the neutral beam heating system from 60 kV to 100 kV. In JET, the resonance position of the ICRH heating system was moved by changing the launch frequency so that on- and off-axis heating was compared. The two machines respond in very different ways to the change in heat deposition profile, consistently with the differences in profile consistency reported above. In

AUG, both the ion and electron temperature profiles are virtually unchanged with the two neutral beam injection energies, despite a factor of two variation in the heat flux calculated at the plasma mid-radius. The deduced heat diffusivity therefore increases by a factor of two in going from the less central power deposition (60 kV beams) to the more centrally heated plasma (100 kV). In the JET comparison pulses, on the other hand, the discharge with central ICRH heating has a significantly more peaked temperature profile. The deduced effective heat diffusivities are, within the experimental uncertainties, identical in the two cases despite a heat flux variation of a factor of two at mid-radius. Again, different transport regimes in the two machines are implied. It would clearly be desirable to perform similar experiments in JET in conditions where profile stiffness of the type reported in AUG is observed.

4. HIGH DENSITY LIMIT

In order to achieve the required fusion yield, any next step machine needs to operate at high density. In both ASDEX Upgrade and JET, the energy confinement is seen to degrade as the density is increased by gas or pellet fuelling. At high densities the discharges make a series of transitions from Type I ELMs to Type III ELMs to L-mode and finally to a density limit disruption. In JET, the transition from Type I to Type III ELMs is accompanied by a further drop in edge pressure [20]. By this point, the discharges are in the regime where profile stiffness is observed and the core confinement is also seen to degrade in these high density Type III ELMy discharges.

In AUG, the separation between Type I and Type III ELMy discharges is less clear. The measured pressure gradient in the edge barrier can be as high in Type III ELMy phases as in Type I discharges (Fig.9). Because the temperature profiles are stiff, the increasing edge density and thus decreasing edge temperature lead to a degrading confinement but the degradation is gradual and continuous even as the ELMs change character from Type I to Type III.

The observed trade off between density and confinement can be ameliorated by operating with increased edge shear [21-24]. In this case, the pictures which are emerging from the two machines are very similar (Fig.10(a) and (b)). By increasing the discharge triangularity,

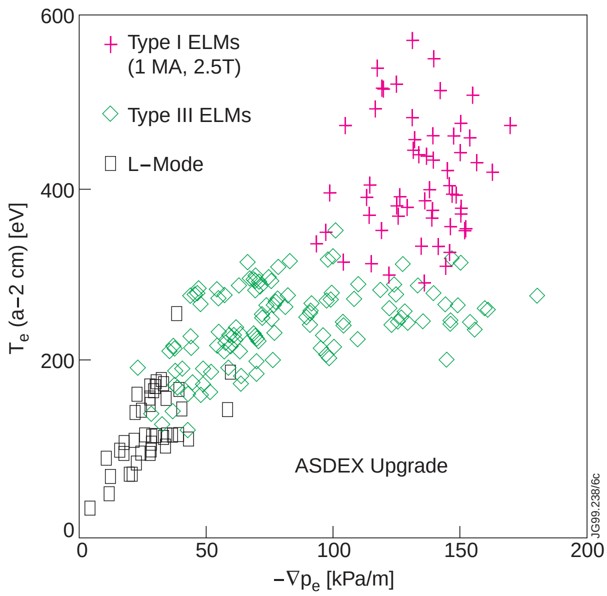

Fig.9: Edge electron temperature versus electron pressure gradient in the edge transport barrier for a series of ASDEX Upgrade pulses. The data are for 1 MA, 2.5 T discharges and are sorted by discharge confinement type.

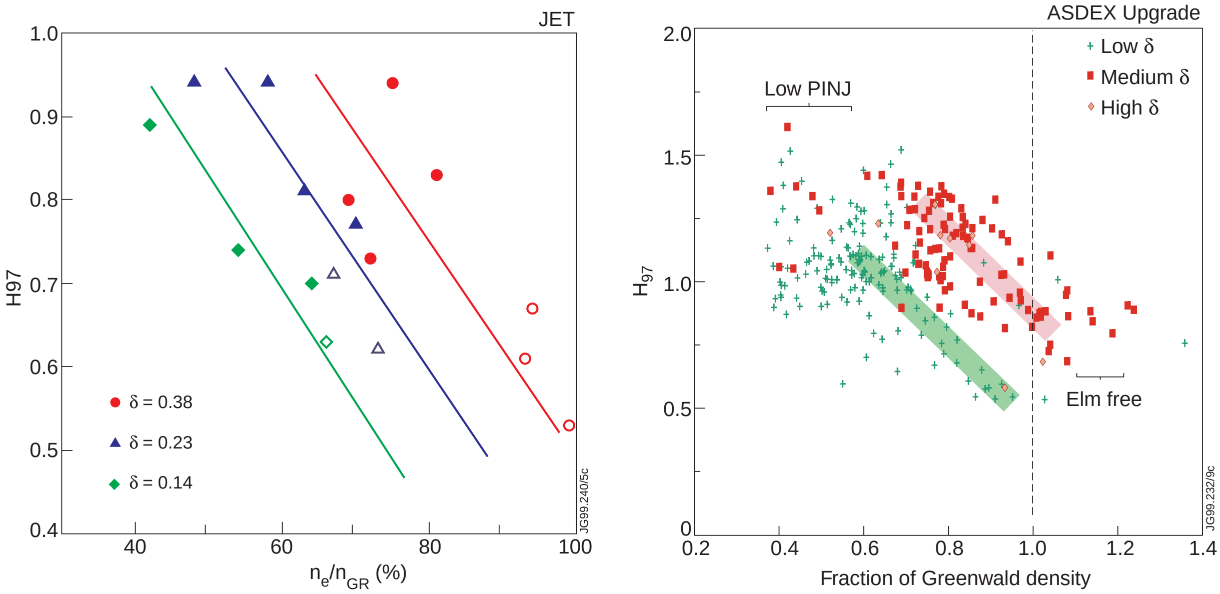

Fig.10: Confinement enhancement factor versus central line averaged density for a series of ELMy H-modes in (a) JET and (b) ASDEX Upgrade. The data are sorted by the edge triangularity of the discharge, showing that access to higher density is possible at the same confinement for more shaped plasmas. The open points in (a) are for Type III ELMy discharges.

it is possible to access higher density. Densities near the Greenwald density [25] have been obtained in both machines. The open points in Fig.10(a) are JET data with Type III ELMs. It can be seen that the confinement penalty for operating in this regime is about 25-30%, relative to the best confinement obtained at lower density.

In order to make extrapolations to a next step device, where operation with smaller Type III ELMs may be necessary in order to protect the divertor targets from excessive erosion, it is necessary to establish the scaling of the transition point between Type I and Type III ELMs. A start has been made on this task at JET by studying the variations of the transition with toroidal field and edge safety factor [26]. The analysis of this experiment was based on the assumption that the Type I to Type III transition occurs at a constant value of edge collisionality. By combining this collisionality limit and an ideal mhd limit for operation with Type I ELMs, the authors make predictions for the scaling of the transition, scalings which depend on further assumptions on the scaling of the cross field transport in the plasma boundary. Assuming a scaling for the cross field transport based on a collisional skin depth model, the Type I to Type III transition is predicted to scale as $B / q_{95}^{5/4}$, in good agreement with the experimental results. The difficulty with this model is that the existence diagram for Type III ELMy discharges in present machines does not show a clear upper limit which scales with collisionality. Instead, the data tend to lie more on a curve of constant temperature or even decreasing temperature on the edge operating space diagram (Figs.1 and 3). If the upper temperature limit for Type III ELMs does scale in the manner predicted by Ref. [10] then one would expect, in the high density limit, a critical temperature for the Type I to Type III transition which scales as β/ν^*. The difficulty with this scaling is that the intersection point with the Type I ELM limit, derived in a similar fashion as described in Ref. [26], in this case scales as $B^{0.94} / q_{95}{}^{2.94}$, in contradiction to the experimental results. Clarification of the dimensionless parameters which are controlling the physics of Type III ELMs is essential if operation in this regime is to be confidently extrapolated to a next step device.

The ultimate H-mode density limit is set by the transition back to L-mode confinement. Again, the picture is very similar from ASDEX Upgrade and JET (Fig.11(a) and (b)). The density which can be obtained in Type III ELMy discharges increases with triangularity and is at or slightly above the Greenwald density in discharges with high shaping.

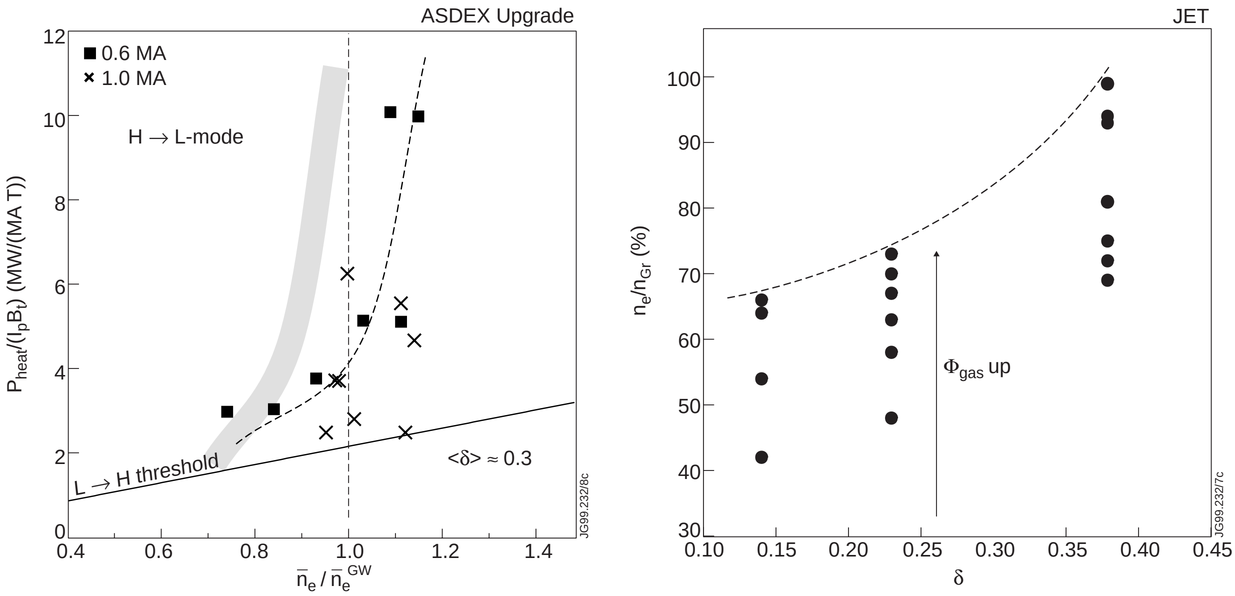

Fig.11: (a) Normalised input power versus the fraction of the Greenwald density limit for transitions from H-mode to L-mode confinement at high density in ASDEX Upgrade. The shaded area represents the region of data from previous Upgrade results at low triangularity (δ~0.2). (b) The fraction of the Greenwald density versus triangularity for a series of gas fuelling scans in JET. The dotted line marks the density at which the discharges made a transition back to L-mode confinement.

5. CONCLUSIONS

Performance near the H-mode power threshold, at low to moderate density, is found to be different in JET and ASDEX Upgrade. In AUG, raising the input power leads to discharges which naturally evolve into Type I ELMs and good confinement (H_{97}~1). In JET, input powers substantially above the H-mode threshold power (P_{in}/P_{LH}>1.8) are required in order to obtain and maintain high confinement. A possible explanation for this difference has been advanced based on the different edge collisionalities of the two machines. In particular, it appears that JET naturally operates in a density range where the critical temperature for the Type III to Type I transition is strongly increased, in line with ideas about the β scaling of turbulence driven by magnetic flutter [10].

In ASDEX Upgrade, the width of the confinement barrier in Type I ELM discharges is measured to remain constant. Thus, the edge confinement does not degrade as the density is increased along this limit. In JET, in contrast, the edge confinement does degrade as the density is raised in Type I ELM discharges. While no edge pressure gradient measurements are available on JET, this degradation is consistent with an edge barrier whose gradient is limited by ideal mhd instabilities and whose width scales in proportion to the edge ion poloidal Larmor radius.

At sufficiently high densities, the core confinement in Type I ELMy H-modes decreases in both machines. This decrease is primarily due to a stiffness of the temperature profiles. Two possible explanations for this stiffness and its absence in high edge temperature JET discharges have been put forward at this conference: transport based on a mixed Bohm, gyroBohm model with a non-local dependence in the Bohm term [16]; and transport variations above the minimum density required for electron / ion equilibration combined with different stiffness in the electron and ion channels [27]. In any case, this decrease in the confinement is not included in the current global energy confinement scaling laws and reliable extrapolation to high density operation in a next step device clearly relies on development of a better understanding of its causes.

At high densities the behaviour of H-mode discharges in JET and ASDEX Upgrade appears to be quite similar. Both machines observe a sequence of transitions from Type I ELMs to Type III ELMs to L-mode to a disruptive density limit as the density is raised. Operation with Type III ELMs implies a 25-30% reduction in the energy confinement, as compared to the best confinement which can be obtained at lower densities. On a more positive note, the maximum density for operation with both Type I and Type III ELMs is substantially increased when the edge magnetic shear of the discharge is increased. Densities at or above the Greenwald limit have been obtained in steady state conditions at high triangularity.

REFERENCES

[1] Kaufmann, M. et al., “Overview of ASDEX Upgrade Results”, in Fusion Energy 1996 (Proc. 16th Int. Conf. Montréal, Canada, 1996), volume 1, p.79, Vienna, 1997, IAEA.

[2] Suttrop, W. et al., Plasma Phys. and Controlled Fusion **39** (1997) 2051.

[3] ITER Confinement Database and Modelling Working Group (presented by J.G. Cordey), Plasma Physics and Controlled Fusion **39** (1997) B115.

[4] Doyle, E.J. et al., Phys. Fluids B **3** (1997) 2300.

[5] ITER Confinement Database and Modelling Expert Group (presented by T. Takizuka), “Threshold Power and Energy Confinement for ITER”, in Fusion Energy 1996 (Proc. 16th Int. Conf. Montréal, Canada, 1996), volume 1, p.603, Vienna, 1997, IAEA.

[6] Sartori, R. et al., “Confinement Loss in JET ELMy H-modes”, Paper P1.022, this conference.

[7] Gruber, O. et al., Phys. Rev. Lett. **74** (1995) 4217.

[8] Pogutse, O., Igitkhanov, Yu., Kerner, W., Janeschitz, G. and Cordey, J.G., “The Alfven Drift-Wave Instability and the Scaling of the Edge Temperature at the L-H Transition”, in Controlled Fusion and Plasma Physics (Proc. 24th Eur. Conf. Berchtesgaden, 1997) vol-

ume 21A, p.1041, Geneva 1997, European Physical Society, Part III.
[9] Horton, L.D. et al., “Dependence of the H-mode Threshold on the JET Divertor Geometry”, Paper P1.021, this conference.
[10] Pogutse, O., Igitkhanov, Yu., Cordey, J.G. and Janeschitz, G., “A Possible Explanation for Type III ELMs in Tokamaks”, Paper P1.036, this conference.
[11] Saibene, G. et al., “The Influence of Isotopic Mass, Edge Magnetic Shear and Input Power on High Density ELMy H-modes in JET”, submitted to Nucl. Fusion.
[12] Itoh, S-I. and Itoh, K., Phys. Rev. Lett. **60** (1988) 2276.
[13] Shaing, K.C. and Crume, E.C., Jr., Phys. Rev. Lett. **63** (1989) 2369.
[14] Bhatnagar, V.P. et al., Nucl. Fusion **39** (1999) 353.
[15] Parail, V.V., Guo, H.Y. and Lingertat, J., Nucl. Fusion **39** (1999) 369.
[16] Taroni, A. et al., “Energy and Particle Transport Modelling with a Time Dependent Combined Core and Edge Transport Code”, in Fusion Energy 1996 (Proc. 16th Int. Conf. Montréal, Canada, 1996), volume 2, p.477, Vienna, 1997, IAEA.
[17] Taroni, A. et al., “Integrated Core-Edge Modelling of Energy Confinement Degradation and Particle Content Saturation in JET ELMy H-modes”, Paper P1.013, this conference.
[18] Stäbler, A. et al., “Influence of Beam Heating Deposition Profiles on the Transport of ASDEX Upgrade Plasmas”, Paper P4.019, this conference.
[19] Christiansen, J.P. et al., “The Plasma Profile Response to Variations of the Heating Profile”, Paper P1.025, this conference.
[20] Lingertat, J. et al., “Characterisation of ELM Triggered Pressure Cycles in JET”, Paper P1.039, this conference.
[21] Saibene, G. et al., “High Density ELMy H-mode Studies at JET in ITER Relevant Scenarios”, in Controlled Fusion and Plasma Physics (Proc. 25th Eur. Conf. Praha, 1998) volume 22C, p.341, Praha 1998, European Physical Society.
[22] Stober, J. et al., “Dependence of confinement and transport on triangularity in ASDEX Upgrade”, Paper P4.009, this conference.
[23] Suttrop, W. et al., “Effect of triangularity variation on edge operational boundaries in ASDEX Upgrade”, Paper P4.010, this conference.
[24] Mertens, V. et al., “Scalings of density characteristics near the Greenwald limit in ASDEX Upgrade H-mode discharges”, Paper P4.008, this conference.
[25] Greenwald, M. et al., Nucl. Fusion **28** (1988) 2199.
[26] Chankin, A. and Saibene, G., “Interpretation of Density Limits and the H-mode Operational Diagram through Similarity Parameters for Edge Transport Mechanisms”, to appear in Plasma Phys. and Controlled Fusion.
[27] Janeschitz, G. et al., “The dependence of energy confinement on the H-mode pedestal temperature”, Paper P4.021, this conference.