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ABSTRACT

Recent results on the understanding and scaling of several of the operational boundaries found in ELMy H-mode plasmas are presented. Divertor geometry is found to be important in determining the H-mode transition power and temperature. Recent experiments from different tokamaks find apparently conflicting evidence for the role of the edge neutral density in controlling the H-mode transition and further intermachine comparisons are clearly warranted. Significant progress has been made both on the understanding and on avoiding the H-mode density limit. Models based on divertor detachment and on MARFE physics reproduce the empirical density limit scalings. The density limit in ELMy H-modes has been increased by changing the profile of the density in the divertor and in the main plasma. Highly radiating ELMy H-modes are currently being studied and display some of the favourable characteristics of the TEXTOR radiated improved confinement (RI) mode.

1. INTRODUCTION

In present day tokamaks, access to the high confinement mode (H-mode) is restricted by several different operational boundaries, including the transition from L-mode, the high density limit and radiation limits. The scaling of these boundaries and indeed the key parameters which control them are sufficiently uncertain as to make extrapolation to a next step machine difficult. Recent experiments in various tokamaks have therefore been targeted at reducing these uncertainties. Other boundaries to ELMy H-mode operation, in particular those related to the ELM instabilities themselves, are reviewed in other papers at this meeting [1,2] and are thus not included in this paper.

It has been recognised for some time that the transition from L to H-mode confinement is controlled by parameters in the plasma edge. A critical edge electron temperature and/or edge ion temperature often correlates very well with the transition to high confinement. However, recent experiments have shown that, in certain circumstances at least, this link is broken and other controlling parameters must therefore be important. The evidence for this and some of the candidate parameters currently being studied are reviewed in Section 2 and their relevance to different machines discussed.

Access to high plasma densities is highly desirable for a tokamak reactor, both from the point of view of maximising fusion power and in order to produce edge plasma conditions compatible with low power and particle loading of the first wall. In present experiments, access to high density in ELMy H-modes is usually accompanied by an unacceptable reduction in energy confinement. Efforts to access high density while simultaneously maintaining high confinement are summarised in Section 3.

An alternative approach to protecting the first wall from unacceptable heat loads is to increase the radiant losses from the plasma by adding a recycling impurity. In TEXTOR, this technique has been shown to also result in improved confinement and simultaneous access to high density, the so-called radiative improved confinement (RI) mode [3]. Recently, attempts have been made in divertor tokamaks to combine the attractive features of the RI-mode with those of the ELMy H-mode. The results of these experiments are reported in Section 4.

2. H-MODE THRESHOLD

In a variety of tokamaks, modifications to the divertor structures have allowed tests of the variation of the H-mode threshold with divertor geometry in otherwise similar conditions. In ASDEX Upgrade, the H-mode threshold was found to be higher, when expressed in terms of global variables, in the new, more closed DIV-II as compared to DIV-I [4]. This difference disappears when the threshold is plotted versus the edge electron density rather than the central line averaged density, again demonstrating that the threshold is controlled by edge parameters.

In JET, where a series of different divertor geometries have been tested, the situation is even more complicated. The H-mode threshold was found to depend not only on the divertor geometrical closure but also on the orientation of the divertor targets and on the proximity of the magnetic X point to the targets [5]. The most extreme example of variations in the H-mode threshold was found in the Mark IIGB (Gas Box) divertor where the threshold was found to be reduced by almost a factor of two when the X point was lowered onto the septum which separates the two divertor legs (Fig.1). In this case the pedestal electron temperature at the time of the transition also decreased by almost a factor of two. Another parameter, in addition to edge temperature, must therefore be important in controlling access to the H-mode in these conditions.

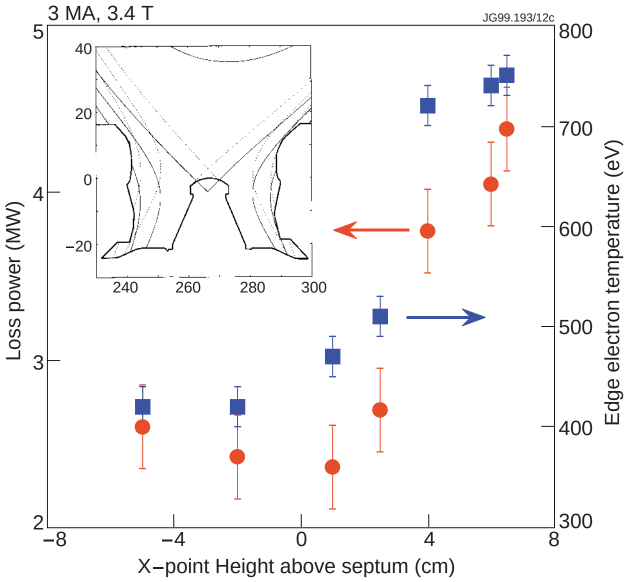

Fig.1: Power necessary to obtain H-mode transitions (squares) and the edge pedestal electron temperature (circles) at the time of the transition as a function of the height of the magnetic X point in JET. Negative X point heights correspond to configurations where the plasma is limited on the divertor septum (see insert) (from Ref. [5]).

Similar results have been reported from DIII-D, in this case relating to the variation in the H-mode threshold when changing the direction of the magnetic field [6]. In Fig.2 are shown various edge parameters in three different discharge conditions: with the ion ∇B drift towards the divertor and at a power level just below the threshold power (solid curves), with the magnetic field reversed and at the same input power as the forward B case (dashed curves) and with reversed B but with the power raised to be just below the (higher) H-mode threshold power (dotted curves). At the same power level, the edge electron temperature, ion temperature and electron density, all measured at the knee at the top of the edge pedestal, are identical in the forward and reversed field pulses. The maximum pressure gradient in the edge plasma is also very similar in these two conditions. The magnetic field direction cannot be controlling the transition through changes in these edge parameters. By contrast, the different field direction caused a factor of three difference in the divertor plasma density (the lower panel in Fig.2). The authors speculate that this large difference may be due to ion ∇B drifts or to ExB flows in the divertor. They conclude that phenomena in the divertor may be critical for the L-H transition.

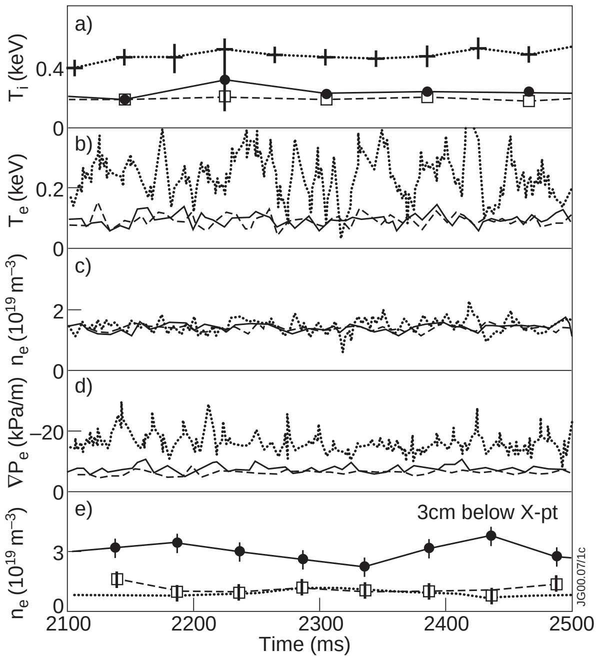

Fig.2: Various edge and divertor parameters in DIII-D in three different L-mode discharge conditions: solid curves - forward magnetic field and 1 MW of input power (just below the H-mode threshold), dashed curves - reversed magnetic field and 1 MW of power and dotted curves - reversed magnetic field and 5 MW of power (just below the H-mode threshold for reversed field). The ion temperature (a), electron temperature (b) and electron density (c) are measured at the knee in the midplane edge profile, the pressure gradient (d) is at the position of its maximum and the divertor electron density (e) is measured 3 cm below the X point (from Ref. [6]).

In DIII-D, the H-mode transition is correlated to the edge neutral density [7]. In the model of ref. [7], the turbulence associated with L-mode confinement is stabilised by shear in the poloidal flow velocity. This flow is, in turn, damped by neoclassical effects and by charge exchange reactions with neutrals in the plasma edge. The authors thus use the ratio of the charge exchange to the neoclassical damping rates to indicate when the edge neutral drag is important. They calculate the edge neutral density using the DEGAS code and come to the counter-intuitive conclusion that the edge neutral density is highest in low density pulses since the increased screening at high SOL density more than compensates the increased neutral source from the wall. Indeed, the increased H-mode threshold observed at low density in DIII-D is calculated to occur at the point where the neutral damping is comparable to the neoclassical damping (Fig.3). Recent measurements of the neutral density in the X point region of DIII-D [8] have confirmed these calculations and lend further support to the conclusion that divertor neutrals may be important in controlling the H-mode transition in low density plasmas where the neutral damping of poloidal rotation exceeds the neoclassical damping rate.

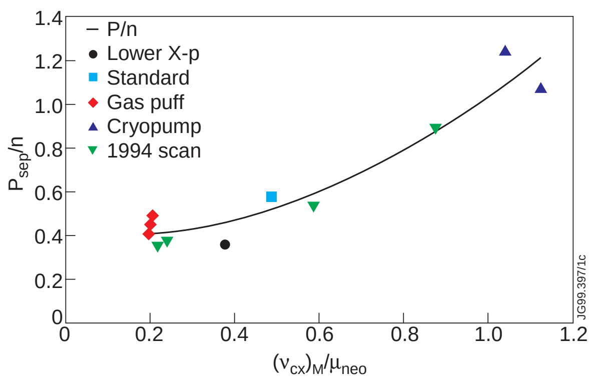

Fig.3: Power flowing through the separatrix in DIII-D at the H-mode transition, normalised to the central line averaged electron density, versus the ratio of the charge exchange to neoclassical damping rates for poloidal flow (from Ref. [7]).

In contrast to these results from DIII-D, careful comparison of the H-mode thresholds on AUG and JET [9] have shown that the transition can be explained by physics based on the Maxwell and Fokker-Planck equations and that recourse to neutral or atomic physics is not required. In these experiments, the plasma current, toroidal field and edge density were adjusted so as to produce plasmas which satisfy the Kadomstev constraints for dimensionally similar discharges [10]. Since the input power is fixed by the occurence of the H-mode transition, only three parameters could be varied and the authors chose to match the edge safety factor, q, andtwo of the three dimensionless plasma parameters: normalised Larmor radius, ρ*,

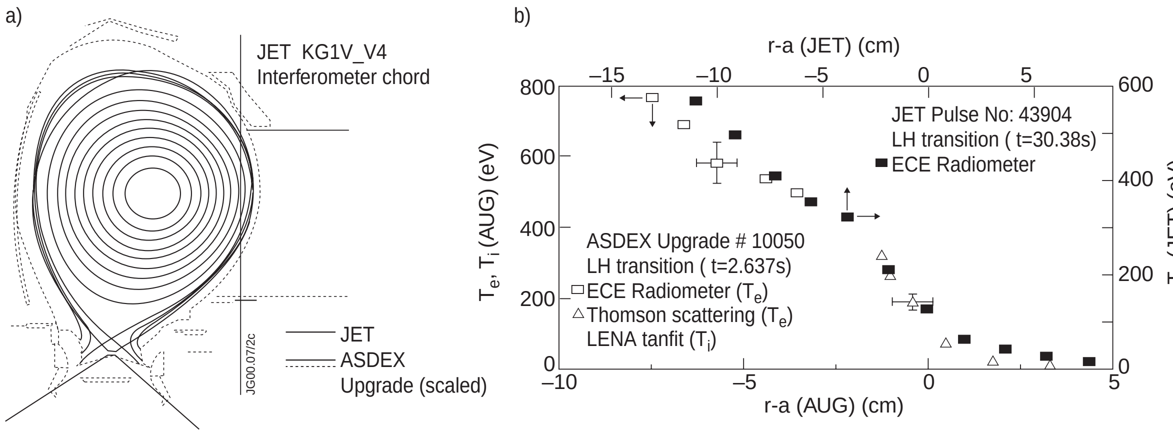

Fig.4: (a) The plasma magnetic geometries used in the JET - ASDEX Upgrade H-mode threshold similarity experiments and (b) the temperature profiles from the two machines just before the transition (from Ref. [9]). Distances are scaled with machine size, a, and the temperatures are scaled as $a^{-1/2}$, according to similarity constraints.

normalised pressure, β and normalised collisionality, ν*. All three pairs of parameters were tested and the value of the collisionality found not to be critical. In Fig.4, the scaled temperature profiles just before the transition in the two machines are shown to be identical within their uncertainties. The authors caution, however, that these identity experiments were possible only at medium collisionalities and other physics such as neutral effects may well become important at both higher and lower collisionality.

An ideal intermachine comparison is that between DIII-D and AUG, since the two are esssentially the same size and no magnetic field scaling is required as in the JET - AUG experiments. In this case, however, the two

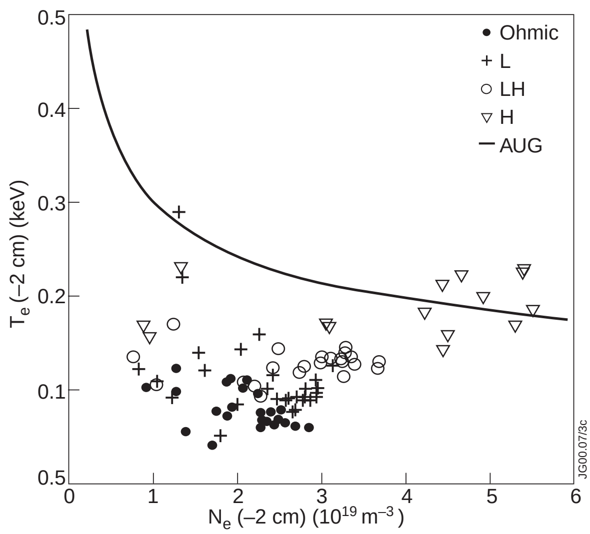

Fig.5: DIII-D L-mode, H-mode and H-mode transition data on the edge operating diagram. The curve is a fit to the ASDEX Upgrade H-mode transition data [11] and shows that the edge electron temperature at the transition is as much as a factor of two higher in ASDEX Upgrade as compared to DIII-D (from Ref. [6]).

machines generally observe a factor of two difference in the H-mode threshold as measured by the edge temperature [6]. This result, which is shown in Fig.5, is strong evidence that parameters other than the edge temperature are important in controlling the H-mode transition.

3. HIGH DENSITY LIMIT

As the density is raised in ELMy H-mode discharges, the confinement is seen to decrease [12-14]. However, both JET and AUG have achieved higher densities for a given level of confinement by increasing the triangularity of the magnetic configuration [15,16]. Typically, as the density is raised, the confinement decreases until a transition from Type I to Type III ELMs is observed. At even higher density, the discharge makes a transition back to L-mode confinement. In JET, the confinement loss occuring when operating with Type III ELMs, which may be desirable from the point of view of first wall power loading, was about 25-30% [15].

In ASDEX Upgrade, the power necessary to maintain H-mode confinement increases strongly as the density is increased to values near the Greenwald density [17] (Fig.6). Recently, Borrass has proposed a SOL-based model of the H-mode density limit which identifies the density limit with complete divertor detachment [18]. In this model, the empirical observations on AUG that the width of the edge transport barrier is approximately constant and that the barrier density gradient is close to the SOL density gradient are used to relate the separatrix density to the density at the top of the edge pedestal. Since this pedestal density is close to the line averaged density in high density ELMy H-modes, the limit on the line averaged density follows from SOL models which fix the separatrix density:

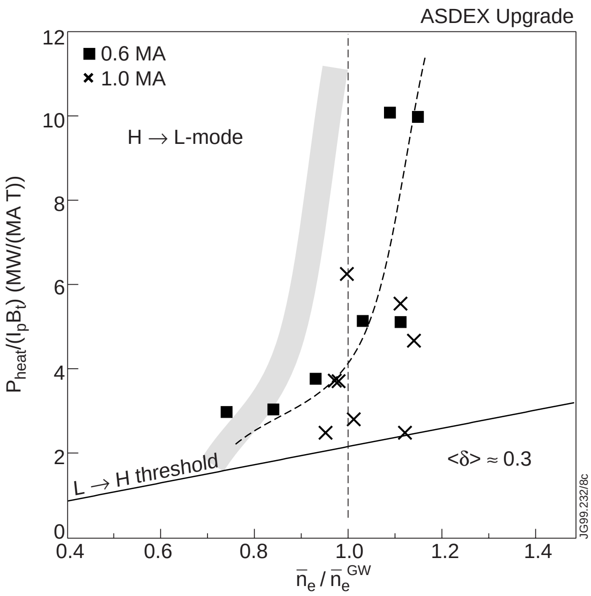

Fig.6: Normalised power required to maintain an H-mode in ASDEX Upgrade versus the central line averaged density, normalised to the Greenwald density (from Ref. [16]). The shaded area represents the data from lower triangularity magnetic configurations and shows the improvement which has been obtained recently with the enhanced shaping capability.

$$\bar{n}_B = 4.14 \frac{q_\perp^{3/32} B_t^{17/32}}{(q_\psi R)^{7/8}} \qquad (1)$$

where $\bar{n}_B$ is the limiting density in units of 10^{20} m^{-3}, $q_\perp$ is the power flow across the separatrix in MW/m^2, B is the toroidal field in T, q_ψ is the safety factor at the 95% flux surface and R is the major radius in m. The normalisation constant was obtained by matching to dedicated density limit experiments in JET and also fits ASDEX Upgrade data well. Eq. (1) is very similar to the Hugill expression of the density limit [19,20]:

$$\bar{n}_H = 1.59 \frac{B_t}{q_\psi R} g \quad (2)$$

where g is a factor which characterises the plasma shape. The main difference between the two limits is in the weaker toroidal field dependence in Borrass' model. Both scalings give similar, good fits to the JET steady state ELMy H-mode database (Fig.7). Dedicated experiments on AUG to study the field dependence of the density limit [16] support the weaker field dependence but the difference between it and the linear dependence is small over the accessible range of toroidal field values.

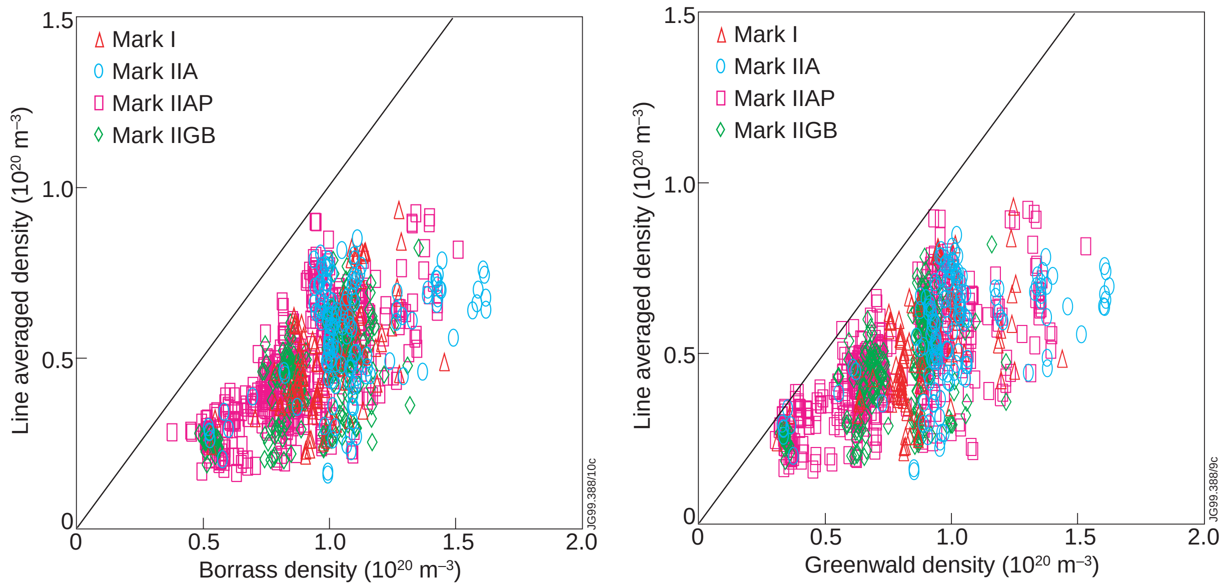

Fig.7: Line averaged density for all of the pulses in the JET steady state ELMy H-mode database versus (a) the density limit based on the model of Borrass and (b) the Greenwald density.

In DIII-D, the H-mode density limit is associated with divertor MARFE formation [21,22]. Using a MARFE stability criterion [23], a scaling for the critical density is derived:

$$\bar{n}_M \propto \frac{I_p^{0.96}}{a^{1.9}} \xi^{-0.11} P^{0.43} R^{0.17} B_t^{0.04} (\kappa^2(1+\kappa^2))^{-0.22} \quad (3)$$

where I_p is the plasma current, a is the plasma minor radius, ξ is the impurity concentration in the plasma, P is the input power and κ is the plasma elongation. Equation (3) is similar to the Greenwald scaling ($\bar{n}_G = I_p / (\pi a^2)$) although with a stronger power dependence. The authors speculate that this power scaling arises due to the global nature of the energy confinement scaling which was used to derive Eq. (3) and which may not be appropriate for edge conditions in highly fuelled discharges. They conclude that a MARFE based limit on the edge density of next generation machines should not be a concern due to the high edge temperatures expected. Furthermore, DIII-D increased the H-mode density limit by control of the fuelling and pumping of the discharge [22]. This control is based on the idea that the limiting MARFE follows divertor detachment and that this detachment is controlled by the neutral pressure in the divertor private flux region [24]. By pumping the private region and fuelling with pellets or gas puffing into the top of the machine away from the divertor, DIII-D obtained simultaneously confinement above the normal H-mode scalings (H_{93}>1) and densities above the Greenwald limit. These results have recently been extended to steady ELMy discharges [25] and are an area of active ongoing research by the DIII-D Team.

The other method which is currently being used to access higher density in ELMy H-mode plasmas is pellet injection from the high field side (HFS) of the torus. In ASDEX Upgrade it has been possible to obtain H-mode plasmas well above the Greenwald density by injecting pellets from the HFS [26]. Modest degradation of confinement (~10%) is observed (Fig.8). The fuelling efficiency from the HFS was higher than for LFS injection. This is thought to be due to acceleration of the high β plasmoid formed around the pellet in the direction of larger major radius [27,28]. Thus, pellet material is displaced towards the edge of the plasma for LFS injection and towards the plasma centre for HFS injection. An example of a comparison between the pellet ablation distance and the final profile of electron density increase is shown in Fig.9 for a DIII-D ELMy H-mode [29]. The large improvement in penetration more than compensates for the slower pellet speeds which typically are achieved with HFS injection.

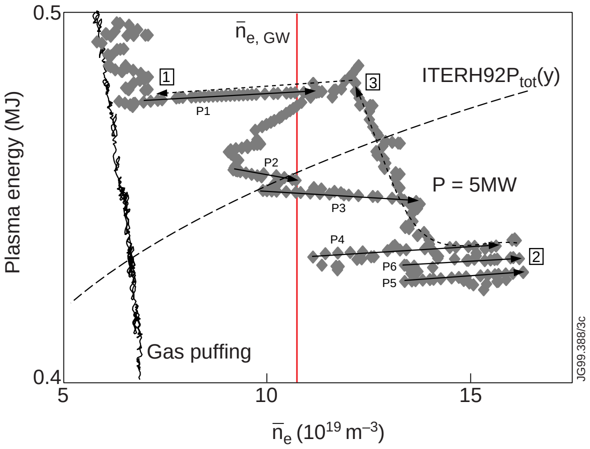

Fig.8: Plasma stored energy versus line averaged density for an ELMy H-mode pulse in ASDEX Upgrade with high field side pellet injection (from Ref. [26]). The Greenwald density and the stored energy predicted by the 1992 ITER ELMy H-mode confinement scaling are shown for comparison. The density rises due to six consecutive pellets, labelled as Pi, for the i'th pellet.

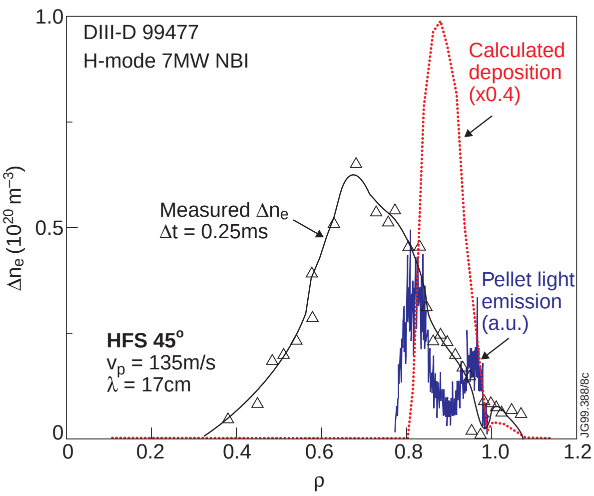

Fig.9: Increase in core plasma electron density as function of normalised minor radius following the injection of a pellet from the high field side of DIII-D (from Ref. [29]). Also shown are the calculated and measured (using Dα emission) pellet ablation profiles.

4. HIGHLY RADIATING H-MODES

Another method for combining high confinement and high density, with the added benefit of reducing the peak power loading on the first wall, is the so-called radiative improved confinement or RI-mode of operation. At TEXTOR, where this technique has been optimised, simultaneous confinement above ELM free H-mode levels and densities above the Greenwald limit have been obtained in limiter discharges with an L-mode edge (see, for example, the review in Ref. [3]). Recently, there have been attempts to combine these attractive features of the RI-mode with those of ELMy H-mode plasmas in divertor tokamaks. On DIII-D RI-like behaviour has been found in ELMy H-mode discharges using neon and argon injection [30]. Regimes have been found where, using a radiating mantle, both the confinement and density can be raised simultaneously (Fig.10). This positive correlation between confinement and density is a signature of the TEXTOR RI-mode and is thus an encouraging sign that the same physics can be transferred to a divertor machine. Current RI experiments at DIII-D are concentrating on making these discharges steady as well as on identifying the underlying physics mechanisms.

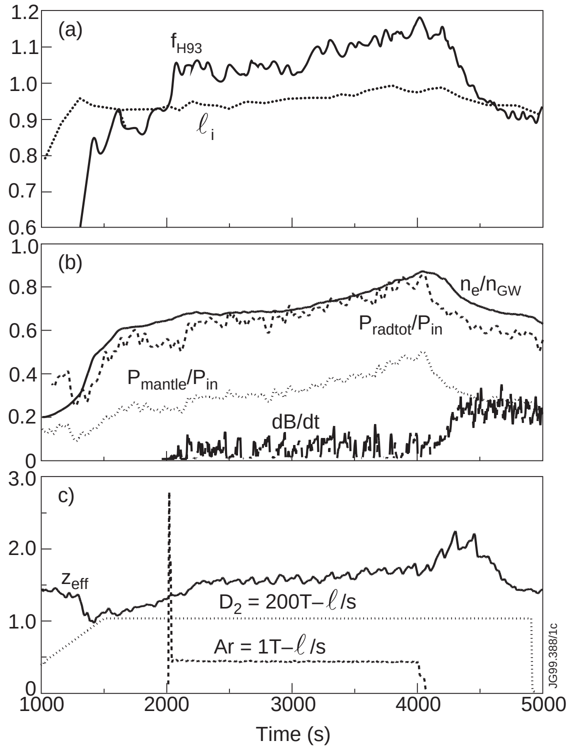

Fig.10: Temporal evolution of a radiating mantle discharge from DIII-D (from Ref [31]). Simultaneous increase in the energy confinement and density is observed when argon is injected into the discharge, a signature of the RI-mode.

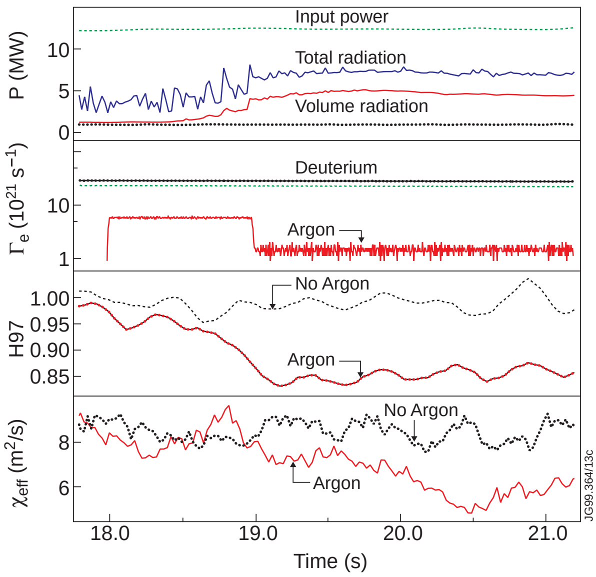

Fig.11: Comparison of the temporal evolution of two discharges in the recent JET RI-mode experiments [32]. A discharge with argon and deuterium fuelling is compared to a reference discharge with deuterium fuelling only. The global confinement degrades, primarily because the edge barrier is weakened, but the effective heat diffusivity in the plasma core actually decreases in the discharge with argon.

Tests of the RI-mode regime have also begun at JET [31]. These preliminary experiments have accessed higher density for a given level of confinement, as compared to unseeded ELMy H-modes, although the relative importance of the RI effect and the special septum limited configuration which was used has yet to be determined. While the global confinement in the JET RI shots was decreased with impurity puffing, the effective heat diffusivity in the plasma core decreased. Thus degradation of the edge confinement, typical of impurity seeded pulses in JET [32] appears to be partly compensated by improved core transport. Futher experiments are planned to optimise the impurity type to be used as a radiator and the impurity and deuterium fuelling rates with the goal of obtaining discharges where the improvement in core confinement exceeds the edge pedestal degradation.

5. CONCLUSIONS

Recent experiments on a variety of tokamaks indicate that the divertor plasma and / or the divertor geometry are often important in determining the power and the edge temperature necessary to obtain H-mode plasmas. Similar results are reported for the new W-shaped divertor at JT-60U in this meeting [33]. Several groups have begun systematic searches for the hidden variables which control the H-mode transition [34,35]. Apparently conflicting results have been obtained as to the importance of neutral charge exchange damping of poloidal rotation in controlling the transition. In particular, low threshold power and edge temperature is observed in JET when the discharge is limited on the divertor septum and the neutral density in the edge plasma is clearly higher than in conventional diverted configurations. This suggests that different mechanisms for controlling the H-mode transition may dominate in the different parameter ranges accessible to present day machines. Clearly, a wider range of comparisons, in particular between different machines, is desirable.

The useful (high) plasma density in ELMy H-modes is limited by a reduction of energy confinement as the density is raised and ultimately by a nearly power-independent H-L limit. These limits can be increased by increasing the plasma triangularity.

Models based on divertor detachment and MARFE formation can produce scalings similar to the Hugill-Greenwald scaling and with as good or better success at reproducing the experimentally observed H-mode limit.

Two methods are currently under investigation for avoiding the H-mode density limit. In DIII-D it has been possible to extend the H-mode density limit by careful control of the fuelling and pumping location, thus reducing the divertor density for a given separatrix density. Furthermore, in both ASDEX Upgrade and DIII-D it has been possible to raise the central density above the Greenwald limit using pellet fuelling from the high field side of the torus, thus achieving high central densities while remaining within the detachment / MARFE limits on the separatrix density. Tests of how the HFS pellet fuelling efficiency scales with machine size are necessary before reliable predictions for a reactor plasma are possible. Such experiments are currently underway at JET.

Recent experiments have been carried out on DIII-D and JET to study the possibility of combining the attractive characteristics of the RI-mode with those of the ELMy H-mode. These experiments, while still preliminary in nature, have produced interesting, positive results which are seen as warranting further optimisation.

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