The Role of Edge parameters for L-H Transitions and ELM Behaviour on ASDEX Upgrade

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Introduction

Local plasma parameters play an important role for transition to high-confinement mode (H-mode) since loss mechanisms which drive the radial electrical field associated with improved confinement [1] critically depend on collisionality and ion temperature and density gradient lengths at the plasma edge. However, partly due to diagnostical difficulties, the clearest picture of L- to H-mode transitions exists so far with respect to global quantities [2, 3]. Few measurements of local parameters have been reported as yet, including an early observation of constant T_e at L-H and H-L transitions on ASDEX [4]. More recent results of JET [5] and of a parameter scan on DIII-D [6] agree on the role of edge temperature as a critical parameter but are ambiguous about the dependence on B_t. Edge Localized Modes (ELMs). always observed during stationary H-mode, impose a stability limit on the edge pressure gradient, but ELM parameters (e.g. ELM type) themselves depend on edge conditions.

Here, we report local T_e, T_i and n_e measurements made at the plasma edge of ASDEX Upgrade at L-H and H-L transitions and ELMs in an attempt to describe the local edge parameter space of L-mode, L-H transitions, and H-mode with various ELM types. A detailed quantitative comparison of edge T_i, n_e, T_e profiles and neutral flux measurements with transition theory for a limited number of dicharges is addressed in a separate paper [7].

For the present investigation, a set of 98 discharges is randomly selected from recent ASDEX Upgrade deuterium discharges with similar geometry (lower single null, ion-∇B direction towards the X-point, $R = 1.65$ m, $a = 0.5$ m, elongation $\kappa \approx 1.7$, triangularity $\delta \approx 0.07$). Varying discharge parameters are $B_t = 1.5 \ldots 3$ T, $I_p = 0.6 \ldots 1.2$ MA, $P_{NBI} = 2.5 \ldots 7.5$ MW, and $P_{ICRF} = 0 \ldots 2$ MW. The set contains shots with and without Neon impurity gas puff. Diagnostics include DCN FIR laser interferometry and Li beam for density measurements, 16-channel Thomson scattering and 45-channel ECE radiometry for electron temperature measurements, and two ionization gauges installed near the divertor and in the main chamber to measure the neutral gas flux.
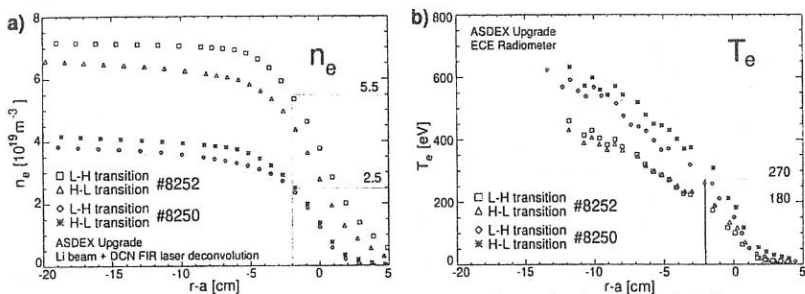

Figure 1: *Comparison of L-H and H-L transitions of two discharges with different line averaged density a) electron density b) electron temperature profiles*

L-H and H-L transitions

We first consider an example to illustrate the relevance of local parameters at the L-H and H-L thresholds. Fig. 1 shows a pair of discharges (ASDEX Upgrade #8250, #8252) with electron density varied and otherwise identical parameters ($B_t = 2.5$ T, $I_p = 1.0$ MA). Slow L-H transitions are achieved by switching a 2.5 MW neutral beam at 34 Hz rate. Line averaged densities (in 10^{19}m^{-3}) / NBI duty cycles at the L-H and H-L transitions are 3.9/50% (#8250, L-H), 7/100% (#8252, L-H), 4/30% (#8250, H-L), and 6.4/30% (#8252, H-L). Edge densities of the two discharges differ by a factor of 2.5 (Fig.1 a). The edge electron temperature (Fig.1 b), taken at 2 cm inside the nominal separatrix, differs by 50% for the two shots, where a higher temperature is found at lower density. The difference in T_e between L-H and H-L transitions is small, of the order of few percent, with the tendency of lower ratio T_e/n_e at L-H compared to H-L.
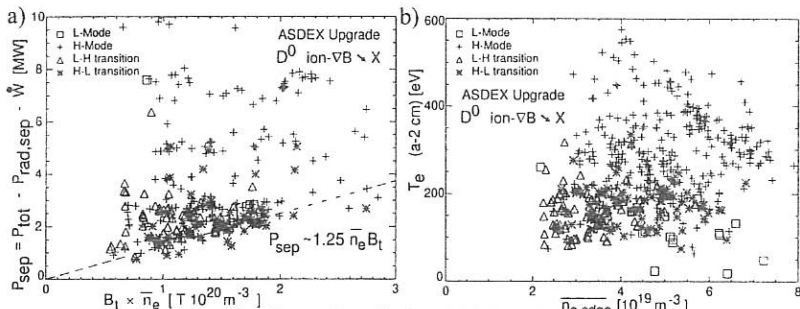

Figure 2: *Comparison of different H-mode threshold dependencies a) P_{sep} vs. $\overline{n_e}B_t$. b) T_e (edge) vs. $\overline{n_e}$ (edge)*

We now compare the global scaling of $P_{sep} = P_{tot} - dW/dt - P_{rad,sep}$ with the dependence of edge T_e on edge density for the set of 98 recent discharges characterized above. Fig. 2 a) shows P_{sep} as a function of $\overline{n_e}B_t$ for L-H, H-L transitions, stationary H-mode, and few L-mode phases with auxiliary heating. The dashed line represents the scaling of P_{sep} (MW) $= 1.25\overline{n_e}$ (10^{20} m^{-3}) B_t (T) derived from earlier ASDEX Upgrade discharges [8]. Although there is a fair agreement with the global $\overline{n_e}B_t$-scaling, several data points depart, which probably reflects the difficulties to determine accurately the fraction of power radiated from inside the separatrix and dW/dt during fast changes of heating power. Fig. (Fig. 2 b) shows a plot of edge electron temperature T_e at $r = a - 2$ cm (obtained by interpolation of two adjacent Thomson channels) vs. edge line-averaged density $\overline{n_{e,edge}}$ for the same data set. A radial position 2 cm (corresponding to $\rho_p = 0.97$) inside the nominal separatrix is selected, because it is believed to be relevant for transition physics but sufficiently distant from the separatrix to avoid T_e being entirely determined by the heat flux to the divertor. There is a large scatter in the T_e data, but no significant dependence on $\overline{n_{e,edge}}$ and also no significant difference in T_e for L-H and H-L transitions is observed. Values of $T_e(r = a - 2$ cm) at the transition center around ≈ 160 eV, with T_e above during H-mode and below during L-mode. H- and L-modes can exist over the entire experimental edge density range of $2 \ldots 7 \times 10^{19}$m^{-3}.

At high neutral densities (main chamber neutral flux $\Gamma_0 \geq 5 \times 10^{21}$m^{-2}s^{-1}). L-modes are

obtained even for high heating power ($P_{tot} = 8$ MW). This illustrates that H-mode can be inaccessible above certain neutral densities. However, since these discharges also have high n_e, high bulk radiation and low edge T_e, it is not exactly clear which mechanism causes this effect.
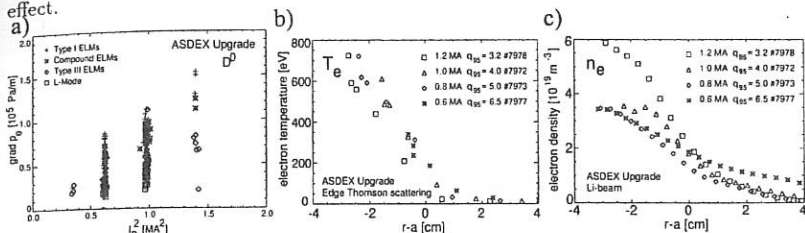

Figure 3: *Scaling of the edge pressure gradient with plasma current: a)* $\nabla p_e(I_p^2)$ *for a set of discharges, b) edge T_e and c) n_e profiles measured for q_a varied by I_p variation.*

Edge Localized Modes

Following the DIII-D classification [9], ELMs of type I and III are observed on ASDEX Upgrade [10]. In addition, compound ELMs exist which are identified as ELM events with subsequent brief transition to L mode [11]. As for pressure gradient driven instabilities, one would expect that edge n, T profiles reflect the stability limit of type I ELMs at [12, 10] and type III ELMs below the ideal ballooning limit [13]. In the first stability region at high shear or in the cylindrical approximation, the normalized pressure gradient $\alpha = 2\nabla p\mu_0 Rq^2/B_t^2$ at the ideal ballooning limit is approximately proportional to the normalized shear $S = (dq/dr) \times (r/q)$ [14]. Assuming that S is approximately independent of q_a, one would expect the maximum $\nabla p = \nabla p_{crit}$ to be proportional to I_p^2 and independent of B_t. This is indeed observed for the set of discharges as shown in Fig. 3 a). For given I_p, highest pressure gradients are observed during type I ELMy H-mode. Pressure gradients in phases with type III ELMs are significantly lower but still above ∇p_e in L-mode. An I_p-scan (Fig. 3 b, c) with otherwise identical parameters ($P_{NBI} = 5$ MW, $B_t = 2.5$ T) reveals that the change in ∇p is almost entirely due to different edge densities, while edge T_e profiles change much less with I_p, consistent with expectation that $\tau_p \propto I_p$. For all discharges except at $I_p = 0.6$ MA gas puff was switched off during H-mode.

Apart from stability limits imposed by ELMs on the edge pressure gradient, the occurrence of the various ELM types can be parametrized by local edge quantities. Fig. 4 a) shows the edge electron pressure gradient normalized to I_p^2 vs. T_e at $r = a - 2$ cm for the set of discharges in deuterium. Type I ELMs mainly populate the region above $\nabla p_e/I_p^2 = 1.5 \times 10^5$ Pa/m/MA^2 and $T_e(a - 2cm) \approx 300$ eV while type III ELMs predominate below. From a plot of T_e vs. n_e at $r = a - 2$ cm (Fig. 4 b) one sees that type III ELMs occur at lower T_e than type I ELMs but both types are observed independent of density. At high resistivity, type III ELMs are destabilized at lower pressure gradient than type I ELMs, while at low resistivity, the fixed stability limit of type I ELMs is reached first, consistent with the picture of a resistive instability [11]. Compound ELMs appear mainly at high edge density (or high neutral gas flux, which is correlated), regardless of B_t, which varies by a factor of 2 in the set. They are found either at intermediate or at low pressure gradient, and can therefore be attributed to type I ELMs or type III ELMs, respectively, followed by a brief L-mode period.
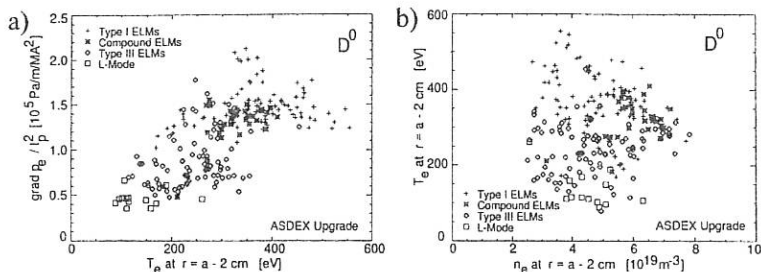
Figure 4: *Occurrence of various ELM types a) $\nabla p_e / I_p^2$ vs. T_e and b) T_e vs. n_e*

Conclusion

On ASDEX Upgrade, T_e at the edge at L-H and H-L transitions is found to be independent of a number of plasma parameters, in particular P_{tot}, B_t, I_p, although there is considerable scatter ($\pm 30\%$) in the data set. Also, no density dependence is obvious from the data set. However, comparison of individual discharges shows that T_e and T_i decrease by $\approx 50\%$ when the edge density is raised by a factor of 2.5. This finding indicates a possible weak dependence of T_e and T_i on density, but also implies that L-H transitions are obtained at very different edge collisionalities. More detailed measurements are necessary to check whether the departure from constant T_e found on other experiments [4, 6] is significant. There is only a weak difference of T_e at the L-H and H-L transitions, indicating that the hysteresis in P_{tot} is owed mainly to the change in confinement. At highest neutral densities, the H-mode is quenched even at high heating powers. This may indicate that an upper limit to neutral densities in H-mode exists, but the mechanism still has to be identified.

A much clearer picture exists with respect to ELMs. As expected for ideal ballooning, $\nabla p_{e,max} \propto I_p^2$ for type I ELMs. ∇p_e is significantly below $\nabla p_{e,max}$ for type III ELMs. The occurrence of ELM types depends on edge T_e, but not density. Consistent with resistive modes, type III ELMs are found at lower T_e than type I ELMs.

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