H-mode and confinement studies in ASDEX Upgrade

W. Suttrop, F. Ryter, V. Mertens, O. Gruber, H. Murmann, H. Salzmann,
J. Schweinzer, and ASDEX Upgrade team,
Max-Planck-Institut für Plasmaphysik,
EURATOM-IPP Association, D-85740 Garching, Germany

Abstract

H-mode operational boundaries and H-mode confinement are investigated on ASDEX Upgrade. The local edge parameter threshold for H-mode holds independent of divertor geometry and changes little with ion mass. The deviation of the H-mode power threshold at densities near the Greenwald limit can be understood as a consequence of a confinement deterioration, caused by "stiff" temperature profiles and lack of core density gradients in gas puff fuelled discharges. Ion and electron temperature profiles can be described by a lower limit of gradient length $L_T = T/T'$.

1. Introduction

The plasma edge, in particular region near the outermost closed flux surfaces, affects in various ways confinement and stability of tokamak operation. Operational limits, such as the boundary between the L-mode and H-mode confinement regimes, onset of MARFE radiation instability, occurence of MHD instability (Edge Localized Modes) can be mapped out in edge parameters, in particular edge temperature and pressure gradient, as reported on the previous IAEA conference [1] from results of ASDEX Upgrade. Since then, ASDEX Upgrade has undergone several modifications, a new, closely baffled "Lyra"-shaped divertor (divertor II, [2]), increased neutral beam heating power of 20 MW and additional diagnostics capabilities. These possibilities have enabled to study the effect of edge parameters in a regime extended towards higher density. Here, we focus on the H-mode boundary and the confinement behaviour for densities approaching the Greenwald density limit [3]. Global and local parameters are compared as they reflect a change in confinement behaviour.

2. H-mode operational limits

The H-mode power threshold in ASDEX Upgrade has been investigated previously in global [4] and local edge [5] parameters. The new divertor II allows to compare the H-mode threshold in ASDEX Upgrade in two divertor geometries. Figure 1 shows the loss power (heating power with change of stored energy subtracted) at the L-mode to H-mode transition as a function of line averaged density $\overline{n}_e$ (a) and edge density $n_{e,edge}$ (b), taken at $r = a - 2$ cm. While the loss power threshold scaling with $\overline{n}_e \times B_t$ differs for the two divertor geometries, the scaling against $n_{e,edge} \times B_t$ is identical. This reflects the observation that in divertor II the density peaking is smaller than in divertor I, i.e. higher edge densities are achieved with the same core density. The local edge parameters, in particular the critical edge temperature for the H-mode transition, has not changed with divertor geometry as figure 1 (c) shows. The edge temperature measured just before the L- to H- mode transition for deuterium at low density (3.8×10^{19} m^{-3}, open squares) is in accordance with the scaling derived in divertor I [5]. The figure also shows profiles with and without use of the newly installed divertor cryompump in both hydrogen and deuterium. Additional pumping has no effect on the transition condition other than by changing the edge density for a given neutral flux and therefore does not modify the scaling. The difference of critical edge temperatures in hydrogen and deuterium at low density is limited to about 20%, whereas the difference in heating power

a) b) c)

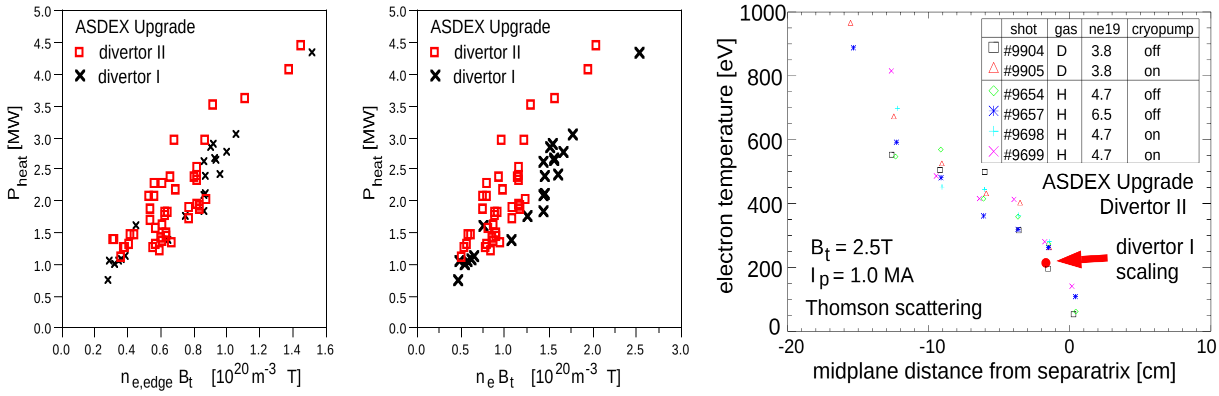

Figure 1: *H-mode threshold in ASDEX Upgrade (a) loss power vs. line-averaged density $\bar{n}_e$ and (b) edge density (taken at $r = a - 2$ cm), multiplied by the toroidal field B_t; (c) edge temperature profiles just before the transition for deuterium and helium in divertors I and II.*

is approximately a factor of two. These comparisons show that the edge parameter threshold scaling is relatively robust and global scalings can be affected by heat and particle transport.

The difference between local and global scalings becomes especially apparent at high densities close to the Greenwald density limit, where the H-mode power threshold increases strongly above the usual $\bar{n}_e \times B_t$-scaling encountered at low and medium densities [6]. With the recently upgraded neutral beam heating of now 20 MW injected power in deuterium a series of high edge density experiments with gas-puff fuelling was carried out. It is found that high edge densities can be achieved only if the heating power is increased proportionally with the total neutral gas influx (external gas flux plus wall recycling).

The operational space at high density and high heating power is mapped out by the trajectories shown in figure 2 (a) in global parameters, heating power vs. neutral gas influx, and (b) in local edge parameters, electron temperature and density at $r = a - 1$ cm (inside the H-mode barrier region). Stable operation at high density is achieved above the boundary labelled “HL” which denotes the H- to L- backtransition. At high edge densities, the backtransition is recognized by a fast drop of the edge temperature gradient, effectively destroying the edge transport barrier [7]. This transition is quickly followed by MARFE extension onto closed flux surfaces. If fuelling is continued, the edge temperature can drop further, leading to tearing mode formation and a disruption, which can be avoided if the heating power is increased to above the “HL”-boundary. A feedback control algorithm has been implemented in the ASDEX Upgrade control system which, after MARFE detection by bolometry, reduces the external gas flux and increases the heating power. With this algorithm, disruptions are avoided reliably in density limit experiments. In ASDEX Upgrade divertor II, at high density the “HL” boundary almost coincides with the onset of strike point detachment during type III ELMs both in global and local edge parameters. Detachment is detected by a drop of *C III* line intensity, a measure of power flux into the divertor. Langmuir probe measurements (I_{sat} at the target plate) reveal that still a particle flux to the target exists during ELMs.

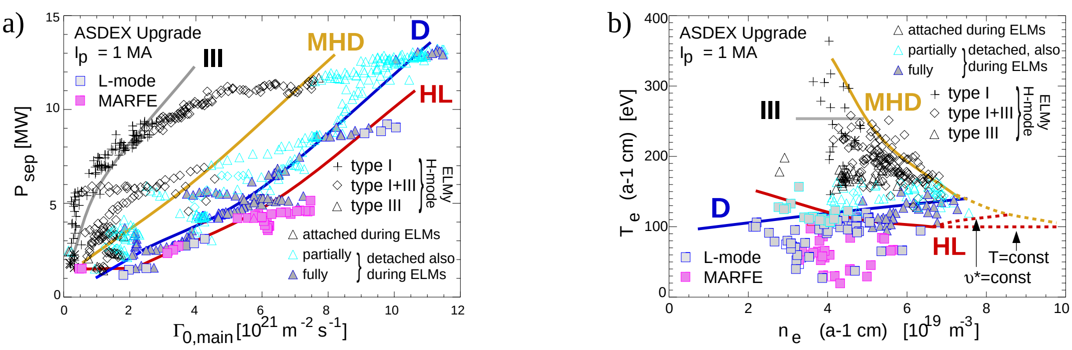

Figure 2: *Operational space at high edge densities: a) separatrix power and main chamber neutral gas flux, b) edge density and edge temperature (taken at $r = a - 1$ cm). Regime boundaries marked “III”, “MHD”, “D”, and “HL” are discussed in the text.*

Nevertheless, the pressure balance at the separatrix between target plate and mid-plane is lost in between and during ELMs. From the edge measurement it is difficult to infer a scaling of the “HL” boundary at the edge. Possibilities are a $T = const$ or collisionality boundary, $\nu^* = const$, in contrast to low and medium densities.

If the heating power is much in excess of the H-mode threshold, the edge temperature increases. If the pressure gradient imposed by ELMs is reached (“MHD” boundary), further increase of edge temperature is accompanied by a reduction of edge density. At sufficiently high edge temperature, small type III ELMs are lost and only type I ELMs can be obtained. Type I ELMs are characterized by lower ELM frequency and larger momentary heat flux during the ELM event. Predictions for the FDR-ITER based on extrapolation of JET and DIII-D data [8], result in a power loss from the main plasma of 25-80 MJ per type I ELM at a frequency of 1 Hz. While detachment during type III ELMs can be achieved, during type I ELMs detachment has not been observed to date, thus a large fraction of the type I ELM energy can be expected to be deposited on the divertor target, which probably leads to an unacceptable peak power load in a reactor-sized plasma.

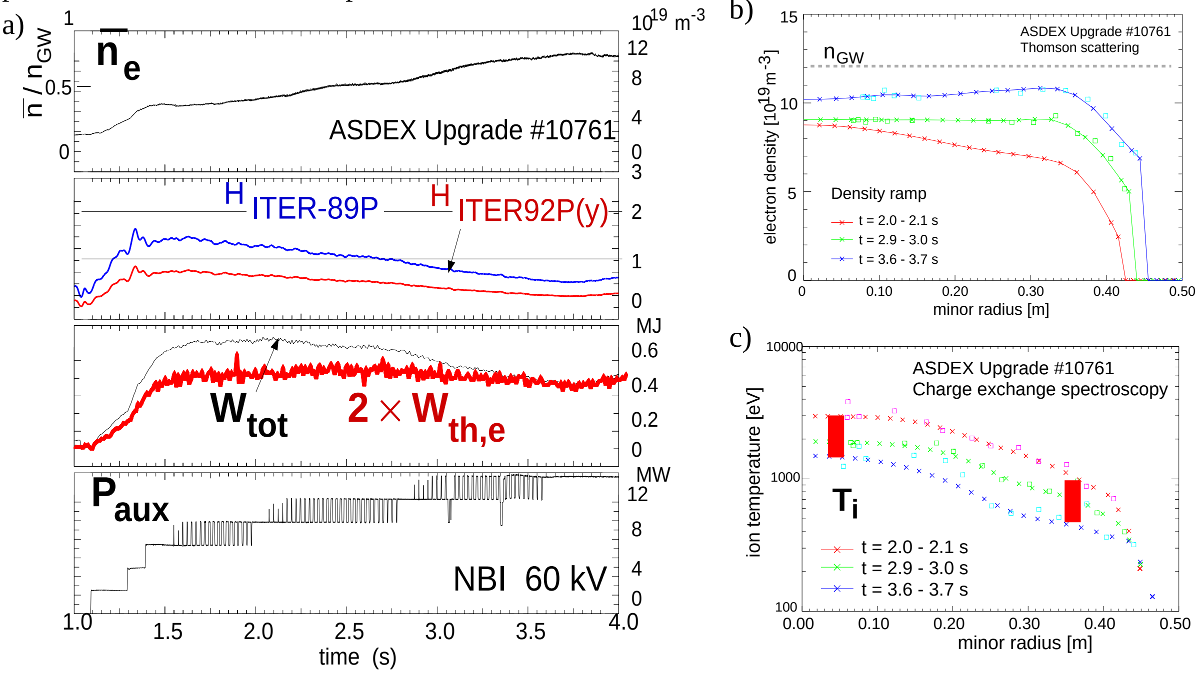

Figure 3: *(a) Time traces, (b) ion temperature and (c) density profiles of an H-mode density ramp experiment. As the density limit is approached, the increasing edge density causes an edge temperature drop. Core temperatures fall proportionally and, together with a flat density profile, the volume integrated pressure (stored energy) decreases.*

3. High power/high density H-mode Confinement

It is generally found experimentally that H-mode confinement depends on plasma density, in particular near the Greenwald density limit a strong degradation compared to the ITER H-mode confinement scalings is found. This is illustrated in figure 3 for a density ramp experiment conducted as described in the previous section. Even with increased heating power, the H-factors relative to L-mode ($H_{ITER89P}$) and ELMy H-mode ($H_{ITER92Py}$) decreases by about 50% when a density of 90% n_{GW} is approached (fig. 3 a). The origin for this degradation can be inferred from the profiles, taken at 3 different times. With increased gas puffing, mainly the edge density increases (fig. 3 b). Due to the limitation of the edge pressure gradient, this requires that the edge temperatures decreases. A profile similarity causes the core temperature to decrease as well (fig. 3 c). Shown is the ion temperature, but electron temperatures show similar behaviour. The logarithmic temperature gradient $L_T = T/T'$ has a lower limit, which is reached at high heating powers that usually lead to H-mode and, at all but highest densities, type I ELMs. The edge density profiles in gas puffed H-mode discharges are typically flat, and the density peaking decreases with increased gas puff, i.e. the core density increases slower than the edge density. Therefore, if the temperature reduction in the core cannot be compensated with a density increase by the same fector, the core pressure, and the stored energy must decrease.

4. Summary and Discussion

At high densities, the edge MHD pressure gradient limit approaches the critical temperature for maintaining an edge transport barrier (H-mode) and avoiding radiation instability. This leaves a narrow parameter space for stable H-mode operation at high density. The intersection of the MHD limit and the H-mode boundary formally defines a maximum edge density which in reality is not achieved experimentally even with high heating power. A model for the density limit based on pressure balance and a heat flux limit that determines the separatrix temperature has been proposed in Ref. [9] to explain the H-mode density limit. A saturation of edge density is predicted which has been observed in JET [9] and ASDEX Upgrade [7] at limited heating power. However, the breakdown of the transport barrier inside closed flux surfaces, a change of radial transport, has not yet been explained conclusively. Simulations of anomalous transport in the relevant parameter regime of drift-Alfven-ballooning instabilities, disagree on whether at high β a transport enhancement with collisionality ν occurs [10] or not [11]. The observed edge-core relation of the temperature profiles leads to a degradation of confinement at high densities. However, one can conceive of several possibilities to overcome this limitation. The ASDEX Upgrade program includes investigations of scenarios with peaked density profiles in the core, e.g. by pellet fuelling from the high-field side [12], spontaneous density peaking during CDH-mode [13,14], and the physics of internal transport barriers [15], with the goal to overcome the limitation of the temperature gradient length observed in the conventional H-mode regime.

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