H-mode Power Threshold Studies at ASDEX Upgrade in Mixed Ion Species Plasmas

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Introduction It is of great importance to understand the dependence of the H-mode power threshold, P_{LH}, on the main ion composition as this is critical for the pre-nuclear operational phase of ITER, which needs to be perfomed with H or He plasmas. A lower P_{LH} in H ($P_{\mathrm{LH}}(\mathrm{H})$) is desired in order to guarantee H-mode operation in the first stage of ITER, when only limited auxiliary heating is available [1]. JET reports on a reduction of $P_{\mathrm{LH}}(\mathrm{H})$ by about 40 % in NBI heated H plasmas with a He concentration of around 5 %. Furthermore, a non-linear increase of P_{LH} with increasing $n_{\mathrm{H}}/(n_{\mathrm{H}}+n_{\mathrm{D}})$ was found [2]. Dedicated experiments were also performed in the latest hydrogen campaign at ASDEX Upgrade (AUG). In the following we present the observations obtained from the AUG P_{LH} studies in H plasmas with He doping and in mixed H-D plasmas.

Experimental Approach The L-H transition has been investigated in pure H plasmas, adding He as a second step and in mixed H-D plasmas, scanning $n_{\mathrm{H}}/(n_{\mathrm{H}}+n_{\mathrm{D}})$. For both P_{LH} studies two different heating schemes were employed, one with a slow ECRH and one with an NBI heating ramp, in order to accurately pinpoint the power across the separatrix at the L-H transition. In the ECRH case the heating was stepwise increased by 200 kW and for the NBI ramp modulated beams of reduced power were used. Two example discharges are shown in figure 1, with the ECRH heating ramp (figure 1 (a)) and the NBI heating ramp (figure 1 (d)). The NBI blips in the ECRH heated cases were needed for diagnostics reasons. In the NBI heated cases central ECRH heating of 600 kW was applied to make sure tungsten accumulation is avoided. All discharges were performed slightly above $\bar{n}_{\mathrm{e,core}} = 4\times10^{19}\mathrm{m}^{-3}$ (see figure 1 (b) and (e)). This is the density where P_{LH} is minimal in D plasmas at AUG [3]. For diagnostics purposes small amounts of N were injected into the plasmas, but not during the very first power ramp, such that an N-free reference is always available. The low-Z impurity content was monitored with CXRS [4]. An independent Z_{eff} measurement from visible Bremsstrahlung gives Z_{eff} values of 1.2 to 1.3 for all discharges except for the discharge with a He concentration of 20 % where Z_{eff} increases up to 1.7. The volume averaged He concentration of the core plasma (up to $\rho_{\mathrm{tor}} \approx 0.9$), c_{He}, was determined with CXRS [5] and $n_{\mathrm{H}}/(n_{\mathrm{H}}+n_{\mathrm{D}})$ within the confined plasma region was measured by means of a neutral particle analyser [6]. The signal of the shunt current measurements of the outer divertor (see figure 1 (c) and 1 (f)) was used to precisely determine the time point of the L-H transition.

Power Threshold in H Plasmas with He Figure 2 (a) shows P_{net} of H plasmas ($n_{\text{H}}/(n_{\text{H}}+n_{\text{D}}) \approx 0.95$) measured in subsequent discharges increasing c_{He} from below 1 % to almost 20 %. The additionally measured N and B concentrations were below 0.1 % and the W concentration was below the detection limit of 0.2×10^{-5}. Due to low core plasma radiation in these discharges the net input power, which is the total input power minus dW/dt, had not to be corrected for radiation losses and thus at the L-H transition $P_{\text{LH}} = P_{\text{net}}$. As can be seen in the figure $P_{\text{LH}}(H)$ is constant with increasing c_{He}. This holds for both the ECRH and the NBI heated cases separately, although for the latter only the range of $c_{\text{He}} \approx 1-5$ % could be investigated. $\bar{n}_{\text{e,core}}$ varies in these experiments from 4.4 to $5.8 \times 10^{19}\text{m}^{-3}$, where the highest densities were reached in the discharges with the highest amount of He. A comparison with P_{scal} from [7] to account for the density dependence of P_{LH} still shows no significant decrease of $P_{\text{LH}}/P_{\text{scal}}$ with He. In contrast, the observation that $P_{\text{LH}}(H)$ stays constant with c_{He} up to 20 % is in line with former observations at AUG, where a decrease of $P_{\text{LH}}(H)$ to $P_{\text{LH}}(D)$ was only seen at $c_{\text{He}} \approx 30$ % [3]. Furthermore, the absolute values of $P_{\text{LH}}(H)$, which lay between 2.2 and 3 MW, are about $2P_{\text{LH}}(\text{D})$ (see also figure 2 (c)), which is consistent with the simple isotope dependence of P_{LH} [8]. Figure 2 (a) also shows that regularly higher values of $P_{\text{LH}}(H)$ are measured for the NBI heated cases. This slight increase of P_{LH} could be due to an increased plasma rotation caused by the NBI torque input [9]. The total torque input caused by the beam blips is negligible for the ECRH heated plasmas, which have a toroidal rotation of about -20 to 20 km/s. In the case of the NBI heated plasmas the total torque input at the L-H transition is about 2 Nm and leads to a toroidal rotation of up to 120 km/s in the central plasma.

Power balance calculations for these discharges with the transport code ASTRA [10] and the NBI code RABBIT [11] indicate a possible additional effect for the increased power threshold. The calculations (see figure 2 (b)) show that the total ion heat flux at the plasma edge, $Q_{\text{i,edge}}$, determined at $\rho_{\text{tor}} = 0.95$, stays constant around a value of 2.2 MW while the electron heat flux, $Q_{\text{e,edge}}$, is systematically lower for the ECRH heated cases compared to the NBI heated cases. The reason for this paradoxal observation is that the electron ion thermal coupling, p_{ei}, is the main contribution to Q_{i} in the ECRH heated cases and it is strongly increased in H plasmas due to its inverse mass dependence. In contrast the main contribution to Q_{i} in the NBI heated cases stems from the direct ion heating, which leads to a reduction of p_{ei} and thus to a higher $Q_{\text{e,edge}}$.

Since at AUG it has been found that $Q_{\text{i,edge}}$ determines the L-H transition [12] and it is constant for all the observed cases, a higher $Q_{\text{e,edge}}$ directly leads to an increased P_{LH}.

Power Threshold in mixed H-D Plasmas Figure 2 (c) shows the dependence of P_{LH} and figure 2 (d) the dependence of $Q_{\text{i,edge}}$ on $n_{\text{H}}/(n_{\text{H}}+n_{\text{D}})$. P_{LH} is determined as the net input power at the L-H transition and $Q_{\text{i,edge}}$ was determined from power balance calculations with the transport code ASTRA and the NBI code RABBIT. For this database of L-H transitions ECRH and NBI heated plasmas with heating schemes as depicted in figure 1 were used. $\bar{n}_{\text{e,core}}$ varied in these discharges from 3.6 to $4.7\times10^{19}\text{m}^{-3}$, which is around the density minimum of D plasmas at AUG. P_{LH} and $Q_{\text{i,edge}}$ show a non-linear behaviour on $n_{\text{H}}/(n_{\text{H}}+n_{\text{D}})$. Both remain constant at the H level up to $n_{\text{H}}/(n_{\text{H}}+n_{\text{D}}) = 0.8$. The absolute values of P_{LH} between 2.2 to 2.8 MW and $Q_{\text{i,edge}}$ between 2 to 2.6 MW are fully consistent with former measurements in H at AUG (compare [13] figure 8) for the given densities. P_{LH} and $Q_{\text{i,edge}}$ are at their D level of about 1.2 MW between $n_{\text{H}}/(n_{\text{H}}+n_{\text{D}}) = 0.55$ and 0. Cases with $n_{\text{H}}/(n_{\text{H}}+n_{\text{D}})$ between 0.8 and 0.55, the region where the transition phase from $P_{\text{LH}}(H)$ to $P_{\text{LH}}(D)$ takes place, have not been achieved yet, which will be the goal of future experiments.

Summary AUG experiments were conducted, investigating the dependence of P_{LH} on mixed ion species in ECRH and NBI heated discharges. A reduction of P_{LH} and $Q_{\text{i,edge}}$ in H by He seeding was not observed with c_{He} ranging from about 1 % to 20 %. It was found that P_{LH} and $Q_{\text{i,edge}}$ have a non-linear dependence on $n_{\text{H}}/(n_{\text{H}}+n_{\text{D}})$. The experiments clearly show that the transition from $P_{\text{LH}}(H)$ down to $P_{\text{LH}}(D)$ takes place between $n_{\text{H}}/(n_{\text{H}}+n_{\text{D}}) = 0.8$ and 0.55.

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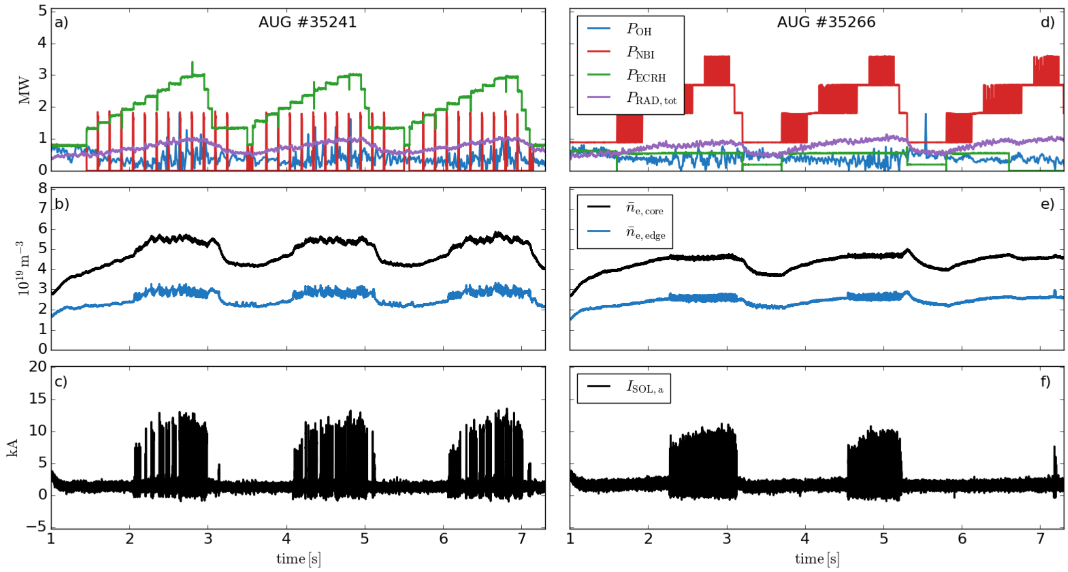

Figure 1: *ECRH (a) and NBI (d) heating scheme for* P_{LH} *in mixed ion species studies discharges, operated at the density minimum of AUG ((b) and (e)) and shunt current signal ((c) and (f)) for L-H transition determination.*

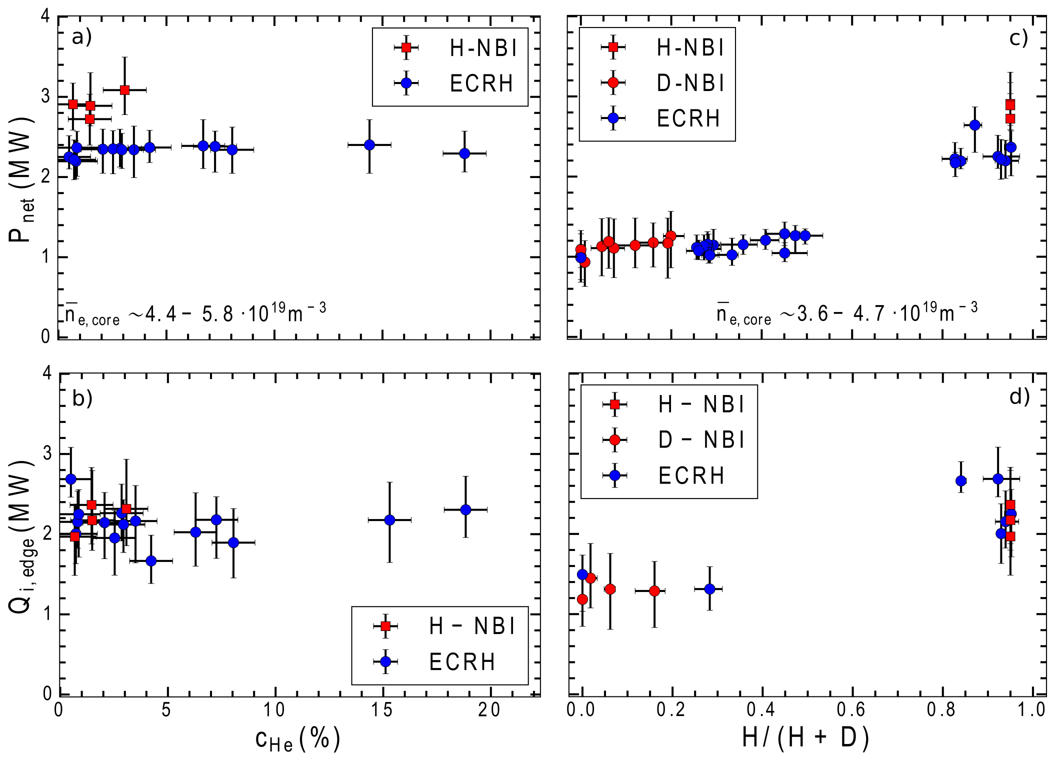

Figure 2: P_{net} *(a) and* $Q_{i,edge}$ *(b) at the L-H transition versus the volume averaged He concentration in %.* P_{net} *(c) and* $Q_{i,edge}$ *(d) at the L-H transition against the relative hydrogen content.*