I-mode studies at ASDEX upgrade

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1. Introduction

The H-mode threshold power, P_{thres}, is well-known to be low when the ion ∇B drift is towards the X-point, while it is about 2 times higher when directed away from the X-point, the so-called unfavourable configuration. In addition, P_{thres} is also about 2 times higher in hydrogen compared to deuterium. These high P_{thres} cases provide conditions to study L-modes over a wider range of heating power. Previous investigation in ASDEX Upgrade, [1, 2], revealed in these scenarios that the power degradation of the confinement time was much weaker than $\tau_E \propto P^{-0.72}$ predicted by the scaling and these plasmas were named "Improved L-modes". The weak power degradation is caused by an increase of the edge temperatures with a concomitant steepening of the gradients, similar to the H-mode pedestal, whereas the density profile almost does not change [3]. Therefore, these plasmas exhibit an edge transport barrier for heat but L-mode particle transport. Recently, such plasmas, re-baptised "I-modes", have been extensively studied in Alcator C-Mod [4, 5]. The same features in heat transport have been observed and the lack of transport reduction in the particle channel is attributed to fluctuations occurring at the pedestal top. Motivated by these studies and by the extended experimental and diagnostic possibilities at ASDEX Upgrade, we also studied the I-mode.

2. Experimental conditions

We made two recent series of experiments with the unfavourable ion ∇B drift: a few ECRH-heated discharges in 2009 in lower single null configuration (LSN) with "reversed" B_T; several discharges in 2011 with the usual B_T polarity, but in upper single null configuration (USN) in which we produced I-Modes with NBI, ECRH or ICRH. An example for each of the series is shown in Fig. 1 together with temperature profiles for comparison between L and I mode. Figure 1a illustrates a LSN case from 2009, heated by ECRH in three steps. The net heating power is defined as usual as $P_{net} = P_{heat} - dW/dt$, where P_{heat} is the heating power taking into account all heating efficiencies. During the first power step (1.5 - 2.0 s) the confinement factor $H_{98y,2}$ remains constant at about 0.5 in agreement with L-mode. During the second ECRH step, 2.0 - 3.0 s, confinement reaches an almost steady state with $H_{98y,2} \approx 0.5$ until about 2.3 s. However, after this time, it increases again up to $H_{98} \approx 0.7$. This is a change from L to I mode which occurs at constant heating power. In contrast to the L-H transition, the L-I transition is not reflected by any change in divertor monitor signal, in agreement with the absence of change in density. In contrast, T_e at $\rho_{pol} \approx 0.95$ increases, leading to the higher plasma energy. Although not measured in these discharges, the 2011 investigations show that, even with ECRH only, the edge T_i behaves similarly to T_e at such medium densities, indicating that both electron and ion heat transport channels at the plasma edge are reduced. The third ECRH step leads logically to a somewhat higher temperature, but $H_{98y,2}$ almost does not increase, this plasma remains in I-Mode at high power. In this discharge the heating power was not high enough to produce a transition to H-mode

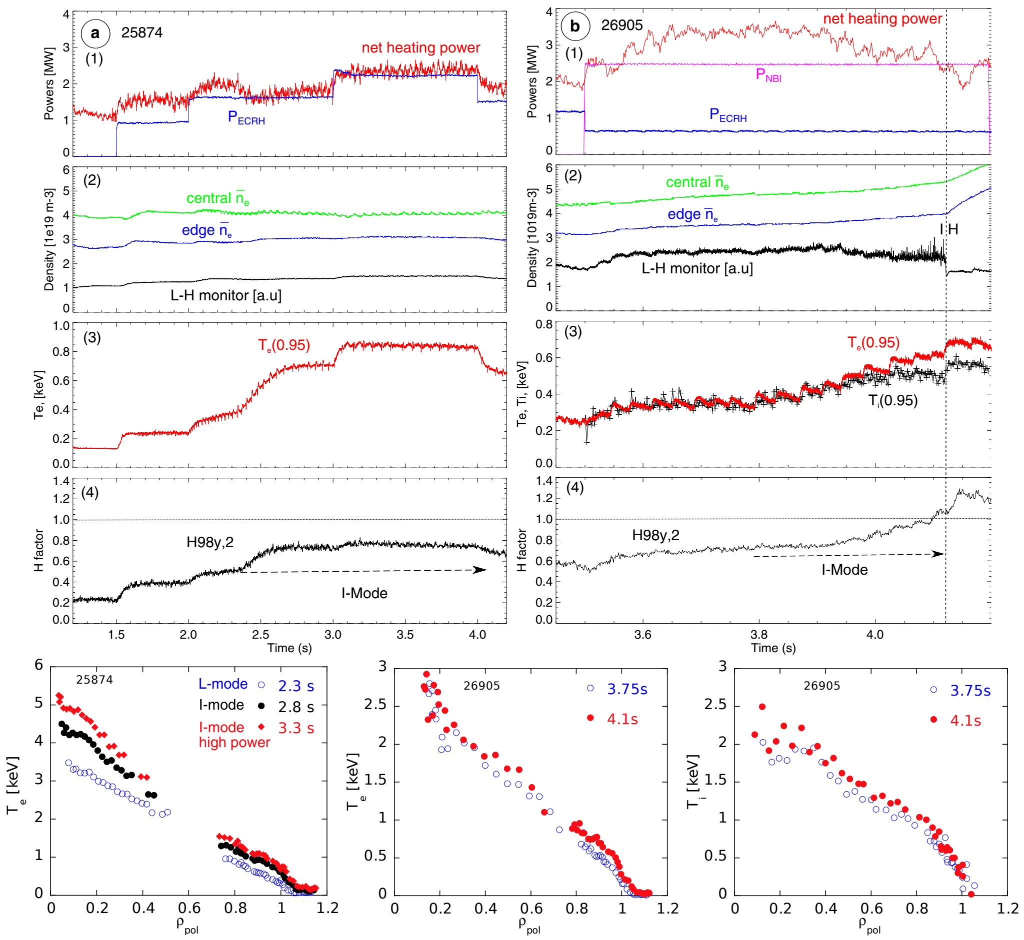

Figure 1: *Time traces of 2 discharges with I-mode: Plot a: LSN configuration with reversed B_T ECRH-heated, no H-mode transition; Plot b: USN with NBI and ECRH, transition to H-mode indicated. Below temperature profiles as indicated in the legend.*

Figure 1b shows a 2011 USN discharge heated by NBI and some ECRH. After the quick increase following the turn-on of the NBI power, $H_{98y,2}$ increases very slowly until t= 3.8 s where it reaches about 0.7. Afterwards, $H_{98y,2}$ starts to increase rather quickly, together with T_e and T_i, to reach about 1.0 at t = 4.13 s where a transition to H-mode occurs, clearly indicated by the divertor monitor and the density increase. During this time interval, P_{net} decreases despite constant auxiliary power which is mainly due to the increase of dW/dt. Therefore, the H-mode transition which occurs at lower power than that of the preceding L and I modes. It seems to be the result of a self-amplifying transport reduction. Indeed, the edge radial electric field well, known to be a key element in turbulence reduction, is weak in the L-mode and increases as the I-mode develops, reaching about -10 kV/m, an intermediate value between L and H mode. This behaviour is also observed with ECRH only (2011 campaign) and, therefore, is not induced by the NBI. In contrast to the first example, in such cases the L-I transition time cannot be identified accurately. As $H_{98y,2} \approx 0.7$ in the steady state time interval 3.65-3.8s, it is possible that it happens before 3.6s. Despite these uncertainties, we define an L-I transition time for each discharge, in this case at 3.8s.

In Alcator C-Mod, the absence of density increase in I-Modes has been attributed to an oscillation concomitant to the existence of the I-mode and located at the top of the temperature pedestal. It disappears in the H-mode. Its frequency increases up to about 300 kHz as the I-mode develops. It is measured in the magnetic signals, as density fluctuations by reflectometry and as T_e fluctuations. In ASDEX Upgrade, reflectometry exhibits density oscillations with very similar characteristics. Magnetic fluctuations, partly correlated with the existence of the I-mode, have also been observed and need further identification.

3. I-mode confinement properties

The operational window for the 2009 and 2011 I-modes is characterised by P_{net} at the L-I and I-H transitions plotted versus density in Fig. 2a. The H-mode power threshold in ASDEX Upgrade for the favourable configuration from [6] is shown as reference. The L-I power exhibits a strong density increase, confirmed by a regression yielding $P_{L-I} \propto \bar{n}_e^{1.68\pm0.3} B_T^{0.65\pm0.3}$. The uncertainties on the exponents correspond to one standard deviation. The P_{I-H} points are lower than P_{L-I} for the reasons explained above but, as expected, above the P_{thres} reference. The high P_{L-I} and its strong density dependence do not support the I-mode as high confinement regime in ITER.

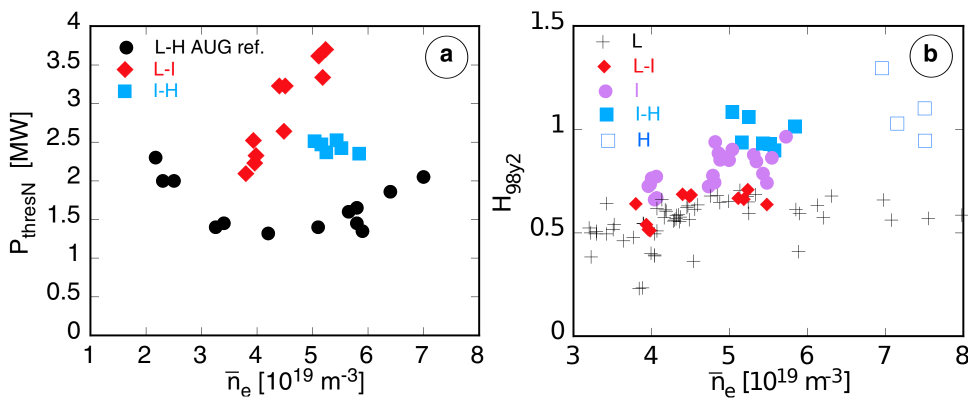

Figure 2: *Plot a: Transition powers: L-H for the favourable configuration (AUG ref.), L-I and I-H transitions. Plot b: $H_{98y,2}$ versus line averaged density for the cases indicated in the legend.*

The confinement properties reflected by $H_{98y,2}$ are illustrated in Fig. 2b for L, I and H modes. The I-mode H_{98} varies between 0.6 and 1.1 without any significant dependence upon density. Therefore, confinement in I-modes reaches that of ELMy H-modes ($H_{98y,2} \approx 1$). However, in our USN experiments, values of $H_{98y,2}$ above 0.7 were only achieved in transient phases which were all evolving to H-modes, as in Fig. 1b, a highly problematic situation in a future reactor. The present dataset suggests that $H_{98y,2}$ does not depend on the heating method NBI, ECRH or ICRH. The improvement in $H_{98y,2}$ is not due to a density peaking which exhibits a trend to be somewhat lower than in L-mode and quite comparable to H-modes at the same collisionality.

4. The I-mode is a general feature

At ASDEX Upgrade, the low density region where P_{thres} strongly increases (see Fig. 2a) has been recently studied in detail in ECRH-heated discharges, in the favourable configuration, [7]. The edge T_e also exhibits a pedestal which develops with increasing ECRH power well below the L-H transition, while density does not increase. At the L-H transition the T_e pedestal does not change. Due to the low density and pure electron heating, the edge T_i increases only very weakly with heating power. The development of the T_e pedestal is reflected in the increasing $H_{98y,2}$. Therefore, such plasma properties are very similar to I-mode. All these observations indicate that the development of edge temperature pedestals, while density does not change, is a general feature in non H-mode plasmas. This effect appears clearly when strong heating can be applied without producing an H-mode transition, i.e. high P_{thres}.

However, in plasmas with low P_{thres} the development of a temperature pedestal and an increase of $H_{98y,2}$ can be also observed, for instance in power ramps used to investigate the L-H transition. As the power range up to the L-H transition is limited, the effect is weaker than in the above cases but visible, as illustrated in Fig. 3a. A power ramp was provided by modulated NBI as shown in panel 1. Density is almost constant until the L-H transition at 1.64s. The 3rd box shows the development of a pedestal before the L-H transition by displaying ∇T_e calculated on each side of the pedestal top. The core-side ∇T_e almost does not change, whereas on the edge side ∇T_e clearly increases during the ramp, reflecting the development of a pedestal. Confinement time also increases during the ramp as indicated by $H_{98y,2}$. Four corresponding T_e profiles are plotted in Fig. 3b: the three profiles before the L-H transition show the gradual development of a pedestal whereas the H-mode point at 1.73s exhibits a stronger pedestal, as expected. Furthermore, P_{net} (panel 1) follows the NBI ramp until about 1.55s where it starts to decrease because the dW/dt contribution becomes stronger than the heating power ramp rate. This is the same effect as described above for the I-mode. This discharge is an example of the standard H-mode performed at the start of every plasmas operation day, [8]. Therefore we have a wide database of such NBI ramps under similar conditions. The clarity of the effect described here varies from day to day but it is overall very reproducible.

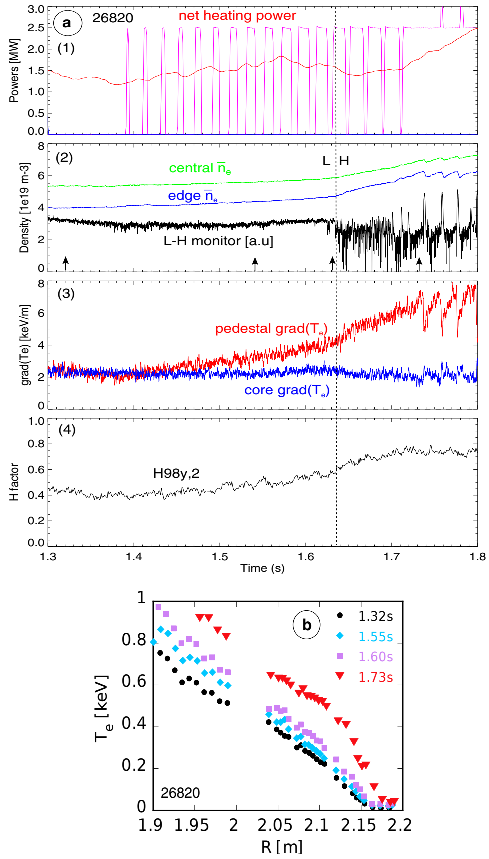

Figure 3: *Plot a: time traces of a discharge with NBI power ramp. Plot b: edge T_e profiles for different times.*

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