ADVANCES IN THE UNDERSTANDING OF THE I-MODE CONFINEMENT REGIME: ACCESS, STATIONARITY, EDGE/SOL TRANSPORT AND DIVERTOR IMPACT

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Abstract

A survey of recent I-mode investigations on the ASDEX Upgrade tokamak is presented. Significant advances have been achieved in establishing robust stationary neutral-beam heated I-modes and the I-mode operational parameter space has been extended towards higher absolute densities and higher Greenwald fractions. Furthermore, detailed divertor investigations show that exhaust power fall-off lengths in I-mode are between those of L-mode and H-mode. Transient divertor heat loads are detected, which are not caused by edge-localized-modes, but by intermittent events first detected in the confinement region. While significant advances in I-mode operation are reported, the discussion also focuses on open questions.

1. INTRODUCTION

The I-mode is an improved confinement regime of tokamak plasmas where an edge transport barrier is observed only in the heat transport but not in the particle transport [1]. This is in contrast to H-mode confinement, which is characterized by transport barriers for both heat and particles. It can be obtained when the H-mode power threshold is kept high, which is usually done by using magnetic field configurations with the ion grad B drift pointing away from the active X-point. The I-mode is benevolent in the sense that it does not exhibit any ELMs [2,3] and no high impurity content or impurity accumulation is observed [4,5]. These peculiar transport characteristics give rise to a multitude of questions, the most prominent being whether the I-mode is a candidate regime for a future fusion reactor and how energy and particle transport can be decoupled. During the last two years, significant advances have been made in the development, characterization and understanding of the I-mode confinement.
regime on the ASDEX Upgrade (AUG) tokamak. The access conditions have been carefully assessed via parameter variations [3] and the edge ion heat flux has been shown to play a key role [6]. Owing to the improvement in confinement, I-modes have often been transient on ASDEX Upgrade. Recent experiments with feedback control on the heating show progress in obtaining stationary I-modes, and the parameter space has been extended to higher densities (Greenwald fractions up to 0.7). Furthermore, the edge pedestal has been investigated in detail. Strongly intermittent density fluctuations of high amplitudes have been detected inside the confined plasma, which end up in the divertor [3, 7, 8].

The confinement improvement in I-mode is accompanied by a deepening of the edge radial electric field well and a reduction of turbulence with respect to L-mode [3, 6]. This reduction of background turbulence leads to the dominance of the so-called weakly coherent mode (WCM) in the density turbulence spectrum [9, 10]. This contribution reports recent I-mode developments from the ASDEX Upgrade tokamak. In particular, the establishment of robust NBI-heated I-modes, which have also been pushed to higher densities (Sec. 2), and the investigation of both stationary and transient I-mode divertor heat loads (Sec. 3) are discussed. At the end, a summary and open questions regarding I-mode are presented (Sec. 4).

2. I-MODE OPERATIONAL SPACE AND STATIONARITY

Recently, a significant step forward in I-mode scenario development has been achieved on ASDEX Upgrade. For the first time, stationary I-modes have been achieved by feedback control on the poloidal plasma beta using the neutral-beam injection (NBI) heating power as the actuator. Apart from enabling a variety of studies, it shows that I-modes can be obtained over several seconds with NBI power, which is an important heating method for future devices. Previously, even though the NBI heating power was maintained constant, the kinetic profiles would develop during up to four confinement times. During this development, the edge turbulence level would decrease and the edge pedestal gradients would grow, until they would be strong enough to cause a transition into H-mode [3, 6, 7]. The fact that edge pedestal gradients develop on such long timescales is particularly interesting.
by putting these results in context with L-H transition studies, and in fact it was found that the I-H transition happens at similar radial electric field strengths as L-H transitions in favorable configuration [7, 11]. The I-modes which develop at constant heating power and transition to H-mode will be called in the following 'non-stationary'. All I-modes which can be maintained for arbitrary long times will be called 'stationary'.

Figure 1 shows a discharge in ASDEX Upgrade in which the average NBI power is ramped in the beginning of the time window. The L-I transition ($t = 2.48$ s) can be observed in the increase of both ion and electron pedestal top temperatures (b) ($T(\rho_{pol} = 0.95)$) and hence also in the plasma energy $W$ (c). Panel (d) shows the $\beta_{pol}$ request value in black and the measurement in magenta. When the $\beta_{pol}$ feedback is switched on, the measurement is above the requested value, and the heating power is immediately reduced. Irrespective of this input heating power reduction, both pedestal top temperatures and the plasma energy continue increasing. During the L-I transition, the density (e) is nearly constant.

In the subsequent I-mode phase, the $\beta_{pol}$ request is stepped three times ($t = 3.1, 3.8$ and $4.5$ s). Both pedestal top temperatures, $T$, and the plasma energy, $W$, follow these steps due to an increase in NBI power. The density is unaffected, which is typical for I-mode. Panels (g) and (h) show the electron temperature and density profiles obtained via the integrated data analysis (IDA) framework [12] for three different time windows. The latter are indicated with vertical bars in Fig. 1(c). The electron temperature increases with heating power in I-mode with respect to the L-mode profile, while the density profile is unchanged. The confinement improvement factor $H_{98}(y, 2)$ [13] is indicated in (c). It is 0.65 for the L-mode time window, and in I-mode it reaches 0.81 and 0.89. On AUG, stationary I-modes are usually observed at $H_{98}(y, 2) < 0.9$ (see also Fig. 2(d)), while at Alcator C-Mod, values of up to 1.3 have been observed [14]. This difference might be due to the higher magnetic field strength of C-Mod, which widens the I-mode existence window in terms of input power. Since power degradation in I-mode is small ($\tau_{E} \propto P^{-0.43}$ on AUG [6] and $\tau_{E} \propto P^{-0.28}$ on Alcator C-Mod [1, 14, 15]) compared to H-mode ($\tau_{E} \propto P^{-0.69}$) [16], this can possibly lead to higher values for $H_{98}(y, 2)$ at high heating power. Of course, this raises doubts on the applicability of $H_{98}(y, 2)$ for I-modes, and it would be reasonable to develop a separate I-mode scaling. Nevertheless, in this paper, $H_{98}(y, 2)$ serves as a means to put the I-mode confinement quality into context with respect to L-mode and H-mode (cf. Fig. 2(d)).

The last $\beta_{pol}$ step, which starts at 4.5 s, results in a heating power increase of 200 kW (cf. Fig. 1(d) and (a)). This increased heating power leads to an I-H transition at $t = 4.82$ s and the increased particle confinement in H-mode results in strongly increasing density (Fig. 1(e)). Figure 1(d) shows that in H-mode $\beta_{pol}$ rises above the request value, which leads to an NBI heating power reduction. Subsequently, the plasma undergoes an H-I backtransition at $t = 4.97$ s. It is worth noting that the I-mode properties from before the H-mode was entered are recovered, which shows the robustness of the I-mode confinement regime. Note also that due to the L-mode like particle confinement of the I-mode, the density is lost quickly after the H-I transition.

The density fluctuation spectrogram measured by reflectometry at $\rho_{pol} = 0.99$ [17] is shown in Fig. 1(f). As soon as I-mode starts, the WCM dominates the spectrum at roughly 75 kHz. During the H-mode phase of the discharge, the density fluctuation level is drastically reduced, but is recovered right after the H-I transition.

The increased robustness of I-mode operation on AUG through the use of NBI $\beta$-feedback operation has been used to increase the I-mode operational space. Figure 2(a) depicts core line-average densities obtained during the last five years of I-mode operation. All data points shown in Fig. 2 are from operation in upper single null. Different phases of the discharges are color-coded: transitions from L-mode into I-mode (‘L-I’, cyan), transitions from I-mode into H-mode (‘I-H’, yellow), and non-stationary (red) and stationary (green) I-modes. For reference, also L-modes (‘L’, black circles) and H-modes (‘H’, magenta triangles) are shown. In 2013 and 2016, I-modes were usually run using NBI-heating, which resulted in predominantly non-stationary I-modes. In 2017, the number of stationary NBI-heated I-modes has been increased due to the NBI $\beta$-feedback control, as is visible in the amount of stationary I-modes on Fig. 2(a). Furthermore, with respect to previous years, significantly higher densities, up to $n_e \approx 7.3 \cdot 10^{19}$ m$^{-3}$ have been obtained in I-mode plasmas.

Figure 2(b) shows the same dataset as in panel (a) but plotted as Greenwald fractions $f_{GW} = n_e/n_{GW}$, with $n_{GW} = I_p (a \pi)^2$, where $n_{GW}$ is the Greenwald density in $10^{20}$ m$^{-3}$, $I_p$ (in MA) is the plasma current and $a$ is the effective minor plasma radius. The Greenwald fractions of stationary I-modes have been increased with respect to previous years. On ASDEX Upgrade, the range of Greenwald fractions is $f_{GW} = 0.58$ in stationary conditions, while transient Greenwald fractions of $f_{GW}$ up to 0.70 have been observed. Experiments are planned for the future to further extend the parameter space.

The increased parameter space in terms of density has allowed the previous AUG parameter studies in I-mode as compared to those described in Ref. [6] to be extended. Figure 2(c) shows the pedestal top electron temperature...
plotted against the pedestal top electron density. L-mode (black circles, 'L') and H-mode (filled magenta triangles, 'H') data points have been included in order to give an overview of the I-mode pedestal existence space. H-modes are situated in the upper right region of the plot, while L-modes are predominantly in the lower right region. The transitions from L-mode to I-mode usually take place between 1 and 2 kPa pedestal top electron pressure, as indicated by the dashed isobars. Both non-stationary and stationary I-modes exist roughly between 1.5 and 3.5 kPa, any higher pedestal top pressure usually leads to an I-H transition.

Figure 2(d) shows the dependence of the confinement improvement factor $H_{98}(y,2)$ on the pedestal top electron pressure $p_e$. Again, the I-mode points are clearly separated: L-I transitions take place at comparably low pedestal top $p_e$ and comparably low $H_{98}(y,2)$ (roughly 0.6). For I-modes (both stationary and non-stationary), $H_{98}(y,2)$ can reach values of up to 0.9. No I-modes with $H_{98}(y,2) > 1$ have so far been observed on AUG.

3. DIVER TOR HEAT LOADS

Any operational regime that is considered as a candidate for future devices, in which the power crossing the separatrix is high, has to be investigated in terms of divertor heat loads. It is especially important to understand the broadening of the heat flux profile, which is usually characterized in terms of the upstream power fall-off length $\lambda_q$. An analysis of $\lambda_q$ in I-mode and its comparison to L- and H-mode values is provided in Sec. 3.1. Moreover, for safe divertor operation, transient heat loads need to be kept to a minimum. For H-mode operation, this is investigated via ELM-suppression through resonant magnetic perturbations [18, 19]. In contrast, I-mode is a natural ELM-free regime [3, 15]. However, since transient bursts have been observed in the confinement region [7]
which end up in the divertor [3], these bursts need to be assessed in terms of divertor heat loads, which is done in Sec. 3.2.

### 3.1. STATIONARY DIVERTOR HEAT LOADS

Heat flux profiles from the outer divertor are shown in Fig. 3 for L-mode (a), two different I-mode time points (b,c), and inter-ELM H-mode (d). The data are inferred from the temporal evolution of the temperature of a divertor tile by solving the heat diffusion equation inside the tile [20]. The temperature is measured with an infra-red (IR) camera. In addition to the inferred heat flux profiles, fits of the form

\[
q = \frac{q_0}{2} \exp \left[ \left( \frac{S}{2 \lambda_q} \right)^2 - \frac{\bar{s}}{\lambda_q f_s} \right] \text{erfc} \left( \frac{S}{2 \lambda_q} - \frac{\bar{s}}{S f_s} \right) + q_{BG}
\]

have been used, which includes an exponential function convolved by a Gaussian. They consider the heat diffusivity in the SOL and the divertor region [21–23]. Here, \( q_0 = q_\parallel/\sin \theta \) is the heat flux at the divertor entrance taking into account the field line angle \( \theta \), \( S \) the divertor broadening, \( q_{BG} \) is the background heat flux, \( f_s \) is the effective flux expansion as defined in Ref. [24]. For the discharge considered and the outer divertor (see fig. 3(a-d)), \( f_s = 7.3 \). For details on the different quantities, refer to Refs. [21, 22].

Comparing the different plots, a gradual narrowing of the heat flux profile is observed from L-mode to I-mode and to H-mode. Furthermore, particularly strong heat fluxes are seen in the “late I-mode” profile (Fig. 3(c)), which is due to transient events observed in the edge confinement region of AUG I-mode plasmas [3, 7, 8]. These “bursts” have been shown to last for comparably short durations of about 50 \( \mu \)s in the confinement region. Nevertheless, they are observed later in the divertor by various diagnostics such as divertor bolometry [3], IR thermography [25] and Langmuir probes. More details on these bursts and their effect in the divertor are reported in the next subsection. Comparison of the H-mode inter-ELM heat flux profile with the L-mode and I-mode profiles shows that the peak heat flux value is significantly reduced in the H-mode (\( q \approx 3 \text{ MW/m}^2 \)). This is due to two reasons. First, some of the plasma energy is expelled via ELMs and here only the inter-ELM heat flux is considered. Second, the core radiation in the H-mode phase of this particular discharge is about a factor of two higher than in L-mode and I-mode, which results in less heat flux crossing the separatrix and hitting the divertor.

The temporal evolution of the upstream power fall-off length \( \lambda_q \) obtained by fitting profiles like the ones from Fig. 3(a-d) is depicted in Fig. 3(e). Here, \( \lambda_q \) obtained from measurements from both inner (●) and outer (△)
divertor are shown. As a general trend, and as observed in Fig. 3(a-d), $\lambda_q$ decreases from L-mode to I-mode and to H-mode. These results are reminiscent of measurements from Alcator C-Mod, where in I-mode $\lambda_q$ is larger than in H-mode [26]. Even though the power fall-off length in I-mode is larger than in H-mode, attached I-modes would still deposit too much power in too narrow a region on a standard divertor in a future fusion device.

For comparison, separatrix density and electron temperature fall-off lengths are shown in Fig. 3(f). They have been measured with the Thomson scattering system [27]. While the electron temperature fall-off length is clearly reduced from L-mode to I-mode, the density fall-off length stays comparable within the error bars. This behavior reminds one of the fact that in I-mode, particle transport is L-mode like while energy transport is reduced. When going from I-mode to H-mode, $\lambda_T$ is slightly reduced, while now $\lambda_n$ changes substantially. The measurements from Fig. 3(f) also show that $\lambda_q \approx \frac{2}{7} \lambda_T$ in I-mode, which leads to the conclusion that the I-mode scrape-off layer is dominated by Spitzer-Härm conductivity.

### 3.2. TRANSIENT DIVERTOR HEAT LOADS

In I-mode, strongly intermittent bursts of density turbulence have been observed in the edge confinement region previously [7, 8] and have been shown to appear later in the divertor [3, 25]. Figure 4 depicts for comparison two turbulence amplitude time traces of 10 ms length measured with Doppler reflectometry in the L-mode phase (a) and in the I-mode phase (b) of a plasma discharge. The Doppler reflectometer was used at fixed frequency, measuring at $\rho_{pol} = 0.99$, which is close to the $E_r$ minimum. The perpendicular wavenumber of the density fluctuations probed is $k_\perp = 12 \text{ cm}^{-1}$. In the L-mode (fig. 4(a)), there is a background fluctuation level, and individual fluctuation events are comparably regular and of low amplitude. In contrast, in the I-mode (fig. 4(b)), the fluctuation amplitude is in general lower, and it exhibits strong irregularly spaced bursts, which are significantly stronger than any fluctuations in L-mode. These intermittent events of high amplitudes deposit energy on the divertor plates, as will be shown in the following.

It is important to characterize a confinement regime not only in terms of stationary heat loads, as in Sec. 3.1, but also to investigate whether there are transient heat loads intrinsically connected to a confinement regime. This is the case particularly for H-mode, in which the divertor has to withstand strong transients caused by the ELMs [28–30]. In I-mode, transient turbulence bursts linked to the WCM have been observed previously [7, 8] and it was shown that these bursts show signatures in the divertor volume observed by absolute extended ultraviolet (AXUV) bolometry [3]. In this section, it is shown that indeed, these bursts cause heat loads on the divertor tiles in both inner and outer divertor.

The pedestal top electron temperature of an AUG discharge going from L-mode through I-mode into H-mode is shown in Fig. 5(a). The improved energy confinement in the I-mode starts at roughly $t = 4.1 \text{ s}$, and about 100 ms later a new stationary state is reached. Note that when the new pedestal top $T_e$ is reached, small dips appear in the time trace, suggesting that some transient losses of temperature take place. At $t = 4.41 \text{ s}$, the plasma goes into H-mode, with better energy confinement. At $t = 4.454 \text{ s}$, the first type-I ELM is seen, which has a much more pronounced impact on the pedestal than the intermittent dips during the I-mode phase of the discharge. The divertor bolometer measurements from outer (pink) and inner (dark red) divertor are depicted in panel (b). As in (a), the L-mode phase is comparably calm, the I-mode shows the intermittent turbulence bursts, and in H-mode,
the type-I ELMs are very pronounced. It has been shown for both Alcator C-Mod [15] and AUG [3] that the I-mode is peeling-ballooning stable and thus the intermittent structures are not type-I ELMs. The heat fluxes onto tiles in the inner and outer divertor are shown in Fig. 5(c) and (d), respectively. As shown before in panels (a) and (b), the L-mode phase is comparably calm, while in I-mode, a more intermittent behavior is observed. For simplicity, three of these intermittent events are marked with orange vertical arrows. These arrows are repeated in (a) and (b) and clearly show that the intermittent heat fluxes onto the divertor target are connected to the intermittent events seen in the bolometry, which are related to the pedestal. Since each intermittent burst lasts only roughly 50 µs, it is difficult to quantify the exact heat flux each burst carries. Nevertheless, Fig. 5 shows that in the I-mode, small intermittent events exist which deposit energy on the divertor. New experiments on AUG are planned to study the potential heat fluxes of individual events in detail.

4. SUMMARY AND OPEN QUESTIONS

The I-mode confinement regime has been investigated and its accessible parameter space has been further extended on the ASDEX Upgrade tokamak. In particular, the robustness of NBI-heated I-mode operation has been significantly increased by incorporating $\beta$ feedback control into I-mode discharges. This development has led to the possibility to increase the density of I-mode discharges, so that Greenwald fractions of 0.58 (stationary) and 0.70 (transient) could be obtained. Experiments are planned to further increase this parameter space. Moreover, and of importance for future devices, the I-mode confinement regime has been characterized in terms of both stationary and transient divertor heat fluxes. In particular, it has been found that the upstream power fall-off length in I-mode is between those of L-mode and H-mode. The upstream power fall-off length scales with the scrape-off layer temperature fall-off length. Apart from stationary heat fluxes, the I-mode does exhibit transient heat fluxes connected to turbulence bursts observed in the confined edge pedestal. At the moment, it is unclear how much energy these bursts carry, so they need to be further quantified. This is planned for the upcoming AUG
experimental campaign. There are several questions about the I-mode confinement regime yet to be answered. At the moment, it is not understood why particle and heat transport are decoupled. The WCM has been put forward as an explanation, yet proof is pending. It is also necessary to quantify the energy carried by the intermittent events in the I-mode edge pedestal in order to estimate the impact on the divertor, and how many particles these events carry. In a broader context and related to future fusion devices, a central question is whether I-modes can be detached or not. Results from Alcator C-Mod show that I-mode detachment might be difficult to obtain [31]. Furthermore, I-modes have not yet been fuelled by pellets. This requirement is important in future reactors. Experiments are planned on AUG in 2018/2019 related to these questions.

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