Stationary ELM-free H-mode in ASDEX Upgrade

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Introduction

The H-mode is usually regarded as the preferable operation regime for a fusion reactor due to its superior confinement properties [1], but it comes with a major drawback: edge-localized modes (ELMs), which limit the achievable edge pressure and lead to unacceptably high heat loads on the divertor plates when extrapolated to large-scale machines [2]. The ELM-free phases traditionally observed in poorly heated H-modes are not a viable solution to this problem due to their transient nature and impurity accumulation. There are several alternative steady-state ELM-free regimes with confinement above L-mode levels, such as the EDA H-mode [3], QH-mode [4] and I-mode [5], but each of them has different advantages and disadvantages and so far there is not a clear winner. Therefore the discovery, study and development of alternative regimes in different machines would be favourable for the successful operation of future reactors. This contribution reports on a stationary H-mode regime without ELMs recently achieved in the ASDEX Upgrade (AUG) tokamak with central electron cyclotron resonance heating (ECRH).

Overview of the ELM-free regime

Figure 1 shows time traces of a discharge with a sequence of ECRH steps followed by a long period with constant heating power, with regime transitions marked by vertical dashed lines. This was a lower single null plasma with the B×∇B drift towards the X-point (favourable L-H configuration), toroidal magnetic field $B_t = -2.5$ T, plasma current $I_p = 0.8$ MA, edge safety factor $q_{95} = 5.4$, elongation $\kappa = 1.7$, average triangularity $\delta_{avg} = 0.24$, and constant deuterium gas puff rate of 2.6×10^{21} e^-/s after the ramp-up. As the heating power is increased the plasma goes from L-mode to an alternation period between L-mode and I-phase at 2.16 s, lasting until 2.22 s, followed by a continuous I-phase with confinement improvement, and transitions to an

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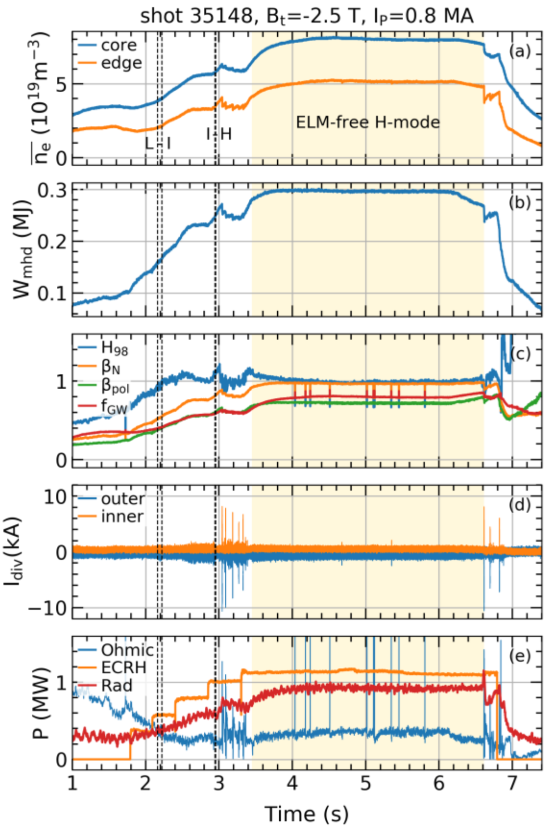

Figure 1: Time evolution of line-averaged electron density (a), stored energy (b), performance indicators (c), divertor currents (d), heating and radiated power (e) in a discharge with a stationary ELM-free H-mode.

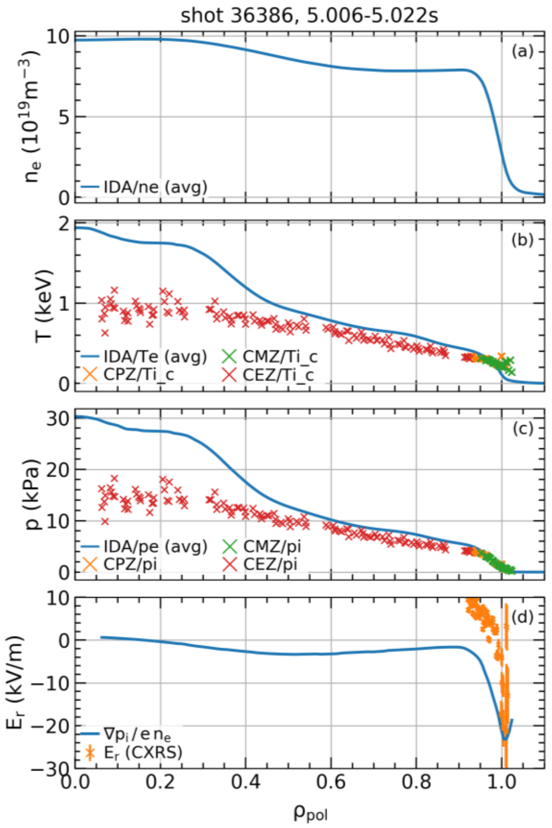

Figure 2: Profiles of electron density (a), electron and ion temperature (b), pressure (c) and estimates of the neoclassical radial electric field (d) during a stationary ELM-free H-mode.

ELMy H-mode at 2.95 s. With another ECRH step the plasma then enters an ELM-free regime at 3.45 s, as evidenced by the divertor currents of figure 1(d), with a significant density (a) and stored energy (b) increase. These stop increasing after less than a second and the plasma remains stationary for about 10 energy confinement times ($\tau_E \approx 0.2$ s) until the end of the flattop, limited in duration only by the inductive current drive.

This ELM-free H-mode can be naturally obtained in AUG without a fresh boronization and has several features which are desirable for future reactors, such as dominant electron heating, low input torque, possibility of existence at low input power, good energy confinement, with an enhancement factor $H_{98y2} \approx$ 1-1.3, high density, with a Greenwald fraction $f_{GW} \approx$ 0.8-0.9, and no impurity accumulation despite the absence of ELMs.

The steady-state ELM-free regime described above is in fact an H-mode and it possesses an edge radial electric field well and pedestal in density, temperature and therefore pressure, as shown in figure 2. The core density profile is flat but the electron temperature and pressure profiles are peaked due to the central heating. The temperature of the ions in the inner core is lower than that of the electrons because only ECRH is applied but they almost equilibrate in the outer core. The electron-ion coupling can in principle be improved by operating at a higher core density. The ability to maintain a stationary edge pedestal without ELMs is likely due to a continuous transport mechanism described in the next section.

Quasi-coherent mode and enhanced transport

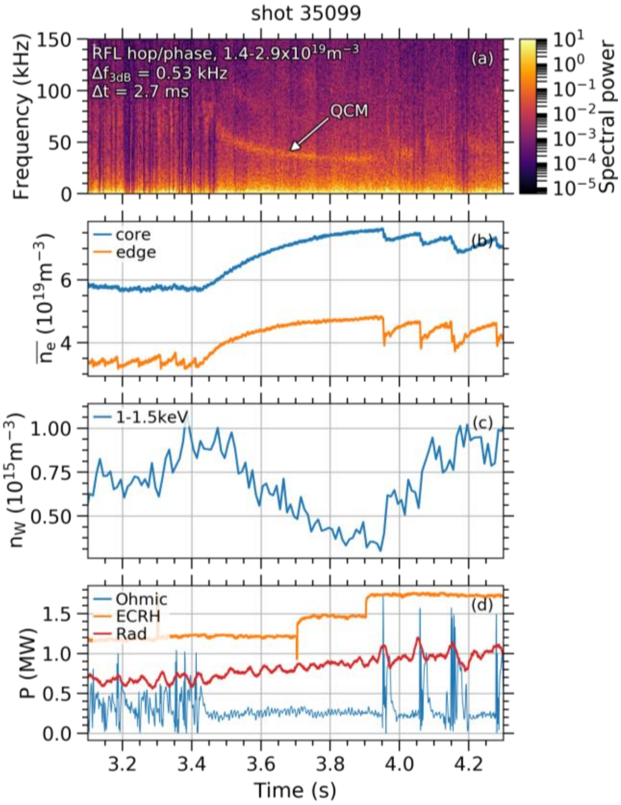

Figure 3: Time evolution of reflectometry phase spectra caused by edge density fluctuations (a), line-averaged electron density (b), tungsten density (c) and heating and radiated power (d) during an ECRH power ramp with an ELM-free H-mode.

The ELM-free regime only exists within a power window above which large ELMs start to appear, as exemplified in figure 3, where sudden density drops are observed in panel (b) after the last ECRH step (d) of a shot similar to the one of figure 1. From 3.45 s to 3.95 s the plasma was ELM-free due to the optimal heating power and there was no impurity accumulation. In fact a strong reduction of the core tungsten density (c) and concentration is observed, even without ELMs to flush impurities. The stationary ELM-free H-mode always features an edge instability which likely provides the required impurity and pressure control crucial for its existence, as opposed to traditional transient ELM-free H-modes which suffer from radiative collapses. This instability is a quasi-coherent mode (QCM) visible during the ELM-free period in the reflectometry spectrogram of figure 3(a), with a broad down-chirping frequency peak from about 70 to 30 kHz as the density increases.

The QCM is an electromagnetic instability whose density fluctuations are measured by several diagnostics on the low-field side, in the steep gradient region of the pedestal and close to the separatrix, moving in the electron diamagnetic direction in the lab frame. Its magnetic signature is detected only by the pickup coils closest to the plasma, probably because of the strong radial decay due to its high mode number (toroidal $n \approx 20$) as estimated with poloidal correlation reflectometry. The QCM seems to be responsible for transport losses as its appearance and disappearance are correlated with changes in edge and divertor parameters [6]. This enhanced transport may be the key to achieving steady-state operation without ELMs and impurity accumulation, as is usually the case in other ELM-free regimes.

Discussion and conclusions

A stationary ELM-free H-mode with several desirable properties has been obtained with ECRH in AUG. This low-torque, dominant electron heating regime exhibits good confinement, high density and no impurity accumulation despite the absence of ELMs, constituting a promising candidate for the operation of future reactors. It shares several features with Alcator C-mod's EDA H-mode [3], for example being obtained with wave heating in a tokamak with a metallic wall and featuring an edge down-chirping QCM which has been shown to produce outward plasma transport [7]. It also shows similar behaviour with some parameter scans not described in this paper, such as an increase of robustness at high triangularity and a lower boundary in density, below which the regime cannot be achieved, resulting in a transient, impurity accumulating H-mode. The EDA H-mode has been extensively studied [8] and developed into a high performance scenario with important achievements, such as the highest volume-averaged plasma pressure ever achieved in a fusion device [9]. Obtaining and studying the EDA H-mode or similar regimes in other machines is therefore extremely relevant to the quest for fusion energy and the stationary ELM-free H-mode achieved in AUG is an important step towards this goal. This promising regime will be the subject of future experiments in order to better understand its physics and scalings, allowing a more reliable assessment of its compatibility with large-scale reactors such as ITER and DEMO.

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