Letter

High-confinement radiative L-modes in ASDEX Upgrade

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Abstract

Experiments have been performed in the ASDEX Upgrade tokamak where plasmas are kept just below the H-mode threshold using feedback on the radiated power via seeded impurity. The resulting high-power L-modes show high confinement properties and no ELM activity due to the reduced pedestal height. The physics of these high-confinement L-modes is explored by means of integrated modeling to clarify the origin of the improved confinement.

Keywords: tokamak, radiative scenario, L mode, dilution, improved confinement

(Some figures may appear in colour only in the online journal)

1. Introduction

So far the standard mode of operation envisaged for a burning plasma is the H-mode [1]. This plasma confinement regime is favourable because of the edge transport barrier formation and the elevated pedestal pressure, leading to relevant fusion power production as desired in a reactor. However, the H-mode is prone to edge MHD instabilities, the edge-localized-modes (ELMs) [2], problematic because of the unsustainable heat loads that these modes eject directly onto the divertor target plates. This motivates the need to explore tokamak plasma scenarios that do not develop ELM activity, particularly in view of future fusion reactor prototypes like the EU-DEMO [3]. These no-ELM scenarios are of various types, characterized by the phenomenology, main actuation, and the plasma parameters obtained. For example, the EDA regime [4–7], e.g. with seeding [8], and the QH regime [9, 10] are mainly H-modes without evident ELM activity. While the I-mode [11, 12] and negative triangularity L-modes [13, 14] have different physics origin.

In this work the focus is put on the regime of high-power, high-radiative L-modes, featuring large amounts of injected core power and simultaneously large amounts of radiated power (mostly in the edge region). These L-modes feature the same global confinement of an H-mode, but at a reduced pedestal elevation, balanced by increased core peaking of the plasma pressure profile. The physics interpretation of this phenomenology is presented here and discussed. Modeling is performed using the ASTRA transport solver [15], coupled to the TGLF turbulence quasi-linear model [16].

In section 2, the experiments are described. In section 3, the modeling results are presented and discussed. In section 4, conclusions are drawn.

2. Highly radiative L-mode experiments

The discharges performed all share some basic engineering parameters: magnetic field $B_T = 2.5$ T, plasma current $I_p = 0.8$ MA, and a line average density of $n \sim 6 \times 10^{19}$ m$^{-3}$. The
heating power is a combination of NBI and ECRH, either injected in feed-forward at fixed amounts, or modulated such as to force the plasma to follow a certain trajectory in normalized parameter $\beta_p$ (ratio of plasma pressure to poloidal magnetic field pressure). In addition, Ar impurity is seeded, injected from the mid-plane valve, to control the net power crossing the separatrix $P_{\text{sep}}$ at a value lower than the expected L–H transition threshold power $P_{\text{LH}}$. Note that this L–H transition scaling is more appropriate for the metallic wall nature of AUG.

The choice of Ar as seeded impurity is due to its property of radiating mainly in the pedestal and SOL regions. The value of $P_{\text{sep}}$ is obtained in real-time with the following formula:

$$P_{\text{sep}} = P_{\text{aux}} - P_{\text{rad}}.$$  \hspace{1cm} (1)

where $P_{\text{rad}}$ is the net radiated power in the core plasma, estimated from bolometric measurements, selecting bolometer line-of-sights that intercept the core plasma [18].

The first example of such an experimental set-up is shown in figure 1, for discharge #37041: the trajectory of $P_{\text{rad}}$ is obtained in the plasma by feedbacking on the calculated $P_{\text{sep}}$, such that it stays below the threshold $P_{\text{LH}}$. The actuator for such a feedback procedure is the mid-plane valve, which is seeding Ar in the required quantity. The main impurity in the plasma is thus Ar, while B and W are subdominant contributors.

Figure 1. For discharge #37041, time traces of: (left) plasma current $I_p$ (enhanced by a factor of 10), averaged density $\bar{n}$, injected ECRH power and NBI power; (right) total auxiliary power $P_{\text{aux}}$, estimated radiated power $P_{\text{rad}}$ inside the separatrix, and calculated separatrix power $P_{\text{sep}}$ and L–H transition threshold power $P_{\text{LH}}$. Bottom panel, left: time traces of effective charge $Z_{\text{eff}}$ (black circles: from Astra simulation at $r/a \approx 0.6$, shown later on, and blue line: estimate from measurements), and Ar seeding rate $P_{\text{Ar}}$. Notice that the value of $Z_{\text{eff}}$ estimated from measurements is using the observed density of Ar$^{16+}$ in the interval $r/a \approx 0.5-0.7$, added on top of a value of 1.3 as base effective charge from B and W. Bottom panel, right: profiles of Ar$^{16+}$ densities at different times.
to both effective charge $Z_{\text{eff}}$ and radiation $P_{\text{rad}}$. The measured Ar density stems from the observation of the Ar$^{16+}$ line [19], which is the dominant one in the radial interval $r/a \approx 0.5–0.7$. Its contribution to $Z_{\text{eff}}$ is estimated as being dominant in the region $r/a \approx 0.5–0.7$, and its added on top of a base of 1.3 given by B and W. The evolution of the density profile of Ar$^{16+}$ is shown too in the bottom-right panel.

The effect of maintaining the power just below the L–H threshold, even when the core power is much higher (a total of $\sim 7$ MW auxiliary power are injected) is shown in figure 2: as can be seen, when the separatrix power drops below the L–H transition threshold power, the ELM activity reduces drastically, and completely vanishes after $t \approx 4.5$ s. The main reason for the disappearance of ELM activity is seen in the right plot of figure 2, where the pedestal top temperature $T_{\text{e,pedtop}}$ clearly drops continuously as radiation increases. This value of the electron temperature is taken at the normalized radius of $r/a \approx 0.9$. On the other hand, the plasma energy, and consequently the H factor, do not drop dramatically. $H \approx 0.95$ stays constant during the ELM-free phase. This unchanged confinement at increasing radiation has also been observed in previous experiments to study H-mode detachment in AUG [20]. How confinement can be sustained despite the loss of the pressure pedestal, is clearly visible in the central temperatures time traces. Both the electron and ion temperatures increase strongly during the ELM-free phase, particularly the ion temperature.

This has its origin in the fact that both the electron and ion (but foremost the ion) temperature gradients are increasing in the region $0.7 < r/a < 0.9$. In figure 3 a clear correlation between the increase of the near-edge gradient and the increase of the temperature peaking is observed.

As a last comment on this discharge: notice that at $t \approx 5.9–6$ s, the discharge disrupts due to a runaway increase of radiated power, not due to increased Ar puff (in fact the Ar puff is decreasing), but due to the non-linear dependence of radiated power on local electron temperature. This runaway phenomenon effectively forces the X-point radiator to move up more into the confined region (it could also be linked to a later-developing MARFE [21] close to the X-point of the plasma), leading to a disruption. The X-point radiator is already observed inside the confined region at $t \approx 4.5$ s, but slowly moves upwards into the pedestal region due to the strong Ar concentration there and the decreased temperature. As such, even though Ar puff is reduced, the plasma is already on a self-destructing path (since the feed-back employed here was on separatrix power, not on radiator position). This development of the X-point radiator is shown in the tomographic reconstruction in figure 4, which clearly shows the penetration of the radiation front deep inside the X-point region by the $t = 5.5$ s time mark. Notice also that poloidally distributed radiation moves more inside the confined region. Infact, while the radiation concentrated close to the X-point is lower at 5.5 s than at 4.95 s, the volume integral in the core region is roughly the same.
Recently, on ASDEX Upgrade, new experimental work has been undertaken to actively control the position of the radiation at the X-point and successfully stabilise it [22], avoiding the disruption caused by the late MARFE formation. Note that modeling of these phenomena has also successfully explained AUG observations in [23].

2.1. Database analysis

Several more discharges have been performed, analogous to #37041, with variations in plasma density and auxiliary power, and target $P_{\text{sep}}$ was also varied. Three of these discharges are shown in figure 5, where the confinement factor $H$ is plotted versus the measured average ELM amplitude, as detected from the divertor currents. It can be seen that, starting from the low-power L-mode phase (empty circles in the low-$H$, no-ELM region), as auxiliary power is increased, the plasma transits into type-I ELMy H-mode (full squares at high ELM amplitude and $H \approx 1$). Then, as the discharge progresses and more Ar is injected to bring the separatrix power below the L–H threshold, the ELM amplitude reduces drastically but the $H$ factor does not. The region at low-ELM activity, but sustained $H$ factor coincides with the region at high radiated power.

As a final note on this section, it is reported here that the value of the $H$ factor computed using the L-mode 89P scaling law, i.e. $H_{\text{L,89P}}$, is estimated at $H_{\text{L,89P}} \approx 1.6$, clearly above typical L-mode values of $\sim 1$.

3. Modeling of the experiments

With the help of the modeling suite ASTRA [15] + TGLF [16], one aim is to understand the physical mechanism behind the unchanged $H$-factor, despite the clear loss of pedestal pressure induced by the injected Ar-driven radiation.

The simulations are set-up in the following way: the profiles of electron and ion temperature $T_e$, $T_i$, and the electron density $n_e$ are evolved according to the injected sources, up to the position $r/a \approx 0.9$, where the boundary condition is set according to the experimental measurement. The simulation follows discharge #37041 in time from $t \approx 2.4$ s to $t \approx 5.5$ s, covering the low-radiation H-mode phase and the high-radiation L-mode phase at the end. The impurity is modeled assuming a concentration of Ar that matches the observed radiation (minus background W radiation which is assumed from fixed W concentration of $2 \times 10^{-5}$). The used signal is supposed to contain the volume integral of the plasma radiated power inside the confined region. The Ar concentration will change in time according to the observed $P_{\text{rad}} \sim P_{\text{rad,W}}$. For the ionization stages, a coronal model is used, based on the scalings offered in [24]. Similarly, the radiated power of Ar is computed using the same coronal model and cooling factors scalings. As such, additional effects like transport [25] or CX [26] are not taken into account. In turn, the Ar influences the density partition since electron density is fixed to the observed value, while D density is obtained from quasi-neutrality after subtracting the Ar contribution. In figure 6, the normalized gradients of electron and ion temperature are shown as a function of time for #37041, evaluated from the simulation at $r/a \approx 0.8$, which is in the location of interest to explain the increase profile peaking.

Aside from running the nominal case described above, another run was performed, where Ar species only contributes to the radiated power, but do not contribute to the particle content. That is, D density is set equal to electron density, and Ar does not cause dilution of D particles. The comparison between the standard case and the latter modified no-Ar case is shown in figure 6. As can be seen, the dilution of D from the Ar particles causes a reduction of transport locally, which allows the gradients to increase, while, in absence of Ar, the gradients do not change as much. Moreover, the ion temperature normalized gradients decreases instead of increasing. In fact, it is well known that the dilution of main ions is a strong stabilizing actor for ion-temperature-gradient (ITG)-driven turbulence [27–29]. For L-mode specifically, it was reported in this letter [31].

Similar experiments and modeling have also been conducted at JET and analyzed as well with ASTRA-TGLF in [30].
4. Conclusions

In this work, new experiments performed at ASDEX Upgrade explore the feasibility of highly-radiative L-modes, with large core auxiliary injected power. The aim was to maintain the net power crossing the separatrix at a lower rate than the L–H threshold. The documented discharges show indeed a reduction of pedestal pressure as radiation from Ar is increased, leading to a complete disappearance of ELM activity.

It is observed that the confinement quality does not reduce even when the pedestal elevation is dramatically reduced by the increase in edge radiation. This is due to a counterbalancing increase in profiles gradients in the near-edge region just inside of the pedestal top.

Through integrated modeling, it is shown that the amplification of the core gradients is linked to the main fuel dilution effect on the ITG caused by the injection of Ar particles.

In terms of relevance for a future reactor, this scenario offers little hope, because one cannot afford to contaminate the plasma core with low and medium-Z impurities such as Ar or Ne. The improvement of performance would not be able to offset the loss of fusion power caused by the core contamination. In fact, the dependence of the fusion power is stronger on the fuel density (square power) rather than on the ion temperature (the dependence on $T_i$ of the DT cross-section decreases monotonically with increasing ion temperature).

Since in a future reactor, like EU-DEMO, the main idea is to seed high-Z impurities in the core (mainly Xe), to reduce the power crossing the separatrix, it is planned to repeat these
experiments using Xe instead of Ar (specifically using Xe-doped D mixture in the gas inlet duct). Moreover, dedicated simulations for EU-DEMO are foreseen to test how much dilution will be actually caused when the impurity injection is such as to keep the power below the L–H transition. Will the dilution in the near-edge region be enough to stabilize turbulence transport proportionally to the loss of pedestal, but at the same time not cause a relevant loss of fusion power? Future studies are aimed at answering this question.

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