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Total number of authors: 465

Published in: Nuclear Fusion

Link to article, DOI: 10.1088/1741-4326/ab2211

Publication date: 2019

Document Version
Early version, also known as pre-print

Link back to DTU Orbit

Citation (APA):

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Dependence on plasma shape and plasma fueling for small ELM regimes in TCV and ASDEX Upgrade

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Abstract. Within the EUROfusion MST1 Work Package, a series of experiments has been conducted on AUG and TCV devices to disentangle the role of plasma fueling and plasma shape for the onset of small ELM regimes. On both devices, small ELM regimes with high confinement are achieved if and only if two conditions are fulfilled at the same time. Firstly, the plasma density at the separatrix must be large enough \( n_{e,\text{sep}}/n_G \geq 0.3 \), leading to a pressure profile flattening at the separatrix, which stabilizes type-I ELMs. Secondly, the magnetic configuration has to be close to a Double Null (DN), leading to a reduction of the magnetic shear in the extreme vicinity of the separatrix. As a consequence, its stabilizing effect on ballooning modes is weakened.

Submitted to: Nucl. Fusion
1. Introduction

To achieve its goals, ITER has to operate in the H-mode confinement regime, specified within the ITER baseline scenario (IBS) \cite{1} for which the key parameters are shown in Fig. 1. Such scenario with good confinement is expected to be accompanied with large type-I ELMs. Therefore, if unmitigated, the resulting steady-state heat fluxes will exceed the material limits of $\simeq 10 \text{ MW} \cdot \text{m}^{-2}$ in ITER size devices and even more so in a demonstration fusion power plant (DEMO). An attractive solution to overcome this limitation is to operate in the H-mode confinement regime with small ELMs such as type-II or grassy ELMs \cite{2, 3, 4, 5}, for which the good confinement is maintained w.r.t. to the type-I regime.

Historically, a distinction has been made between type-II and grassy ELMs: On the one hand, type-II ELMs are observed when increasing the plasma density, edge safety factor and triangularity, moving the plasma close to a double-null (DN) configuration. In addition, the onset of type-II ELMs is accompanied by a broadband fluctuation in the range of 30-50 kHz, observed in the magnetics, microwave reflectometry and electron cyclotron emission diagnostic up to the pedestal top ($0.7 < \rho_{pol} < 0.95$). On the other hand, the grassy ELM regime was found on JT-60U with increased triangularity and high edge safety factor, but at low collisionality, close to ITER-relevant values. And no signature of broadband turbulence has been reported for this ELM regime. The distinction between type-II and grassy ELMs is highlighted in Fig.1 where the typical values of the IBS key parameters are shown.

Nevertheless, it is not clear if the IBS parameters are the key parameters to fulfill to achieve a small ELM regime or if there exist other key ingredients in common between type-II and grassy ELM regimes. It is also of great importance to further assess if a small ELM regime would be achieved in ITER under certain circumstances.

This paper summarizes the results of a series of experiments, conducted in AUG and in TCV to disentangle the role of plasma fueling, plasma triangularity and closeness to the DN configuration for the onset of a small ELM regime, either type-II or grassy (hereafter, the distinction is dropped on purpose). The necessity of a large density at the separatrix is demonstrated in Section 2, while in Section 3, the crucial role of the plasma shape is reported. A physical interpretation, suggesting a prominent role of the magnetic shear is given in Section 4 followed by concluding remarks and outlook (Sec.5).

2. Small ELM regimes and plasma density at the separatrix

2.1. Pellet fueling versus gas fueling in AUG plasmas

In AUG #34462, a small ELM regime is reached at t=3.0 s with strong gas fueling and a plasma shape close to a DN configuration (Fig. 2). The closeness to a DN configuration is monitored by the parameter $\Delta_{sep}$, the distance, at the outboard midplane, between the separatrix and the flux surface through the secondary X-pt ($\Delta_{sep}^{#34462} = 7 \text{ mm}$). At t=4.0 s, while the plasma shape is unchanged, the gas fueling is replaced by pellet injection into the plasma core, maintaining the averaged plasma density. It is observed that the small ELMs are suppressed and the type-I ELMs are fully restored, as clearly seen on the divertor shunt current measurement.

Figure 3 shows the density and temperature profiles for both ELMy phases: small in red and type-I in black. Profiles have been shifted such that $T_{e,sep} = 100 \text{ eV}$. The core fuelling with pellets has almost no effect on the temperature profile. For the plasma
density, the core profile is unchanged up to the pedestal top with $f_{G, pol} \approx 0.85$. The pressure gradient in the pedestal is almost unchanged. Conversely, the SOL profile is strongly affected by the change in the fueling method: while the profile is broad with $f_{G, sep} \approx 0.3$ for strong gas fueling case (small), it becomes narrower for the pellet fueling case and the separatrix density is reduced by a factor of 2 ($4 \times 10^{19} \rightarrow 2 \times 10^{19} \text{ m}^{-3}$).

This is further confirmed with the estimate of the fall-off lengths in the near SOL: with gas fueling, $\lambda_n$ is increased by more than a factor of 2 and $\lambda_p$ increases by 33%. A reduced pressure gradient around the separatrix means that the pedestal width is shrunk which in turn increases the stability of type-I ELMs. Further details on this scenario can be found in Ref. [6].

It has been observed on MAST [7] that the filamentary transport at the foot of the pedestal is significantly changing from type-I to type-II. Also, for AUG #34462, a change in the turbulent transport is revealed from Doppler Back Scattering measurements just inside the separatrix ($\rho_{pol} \sim 0.99$). Figure 4 shows a 500 $\mu$s long time series of DBS signals (real part) measured within both phases. For the small ELM regime (DN and gas fueling, red), the DBS signal shows large bursts in amplitude. These bursts, in the range of 40-80 kHz, are much more frequent than in between type-I ELMs later in the discharge (close to DN and pellet fueling, black) [8]. Further investigations are needed to clarify the change in the turbulent transport between both ELM regimes but it suggests a correlation with the filamentary transport in the scrape-off layer close to the H-mode density limit [9].

2.2. Gas fueling scan in ELMy H-mode in TCV

A reliable scenario for type-I ELMy H-mode in TCV is obtained with the following parameters: Lower Single Null, $I_p = 140$ kA, $B_T = 1.4$ T, $\kappa = 1.5$, $\delta = 0.38$, $\Delta_{sep} = 24$ mm, $q_{95} = 4.5$, $P_{NBI} = 1$ MW ($P_{L-H} \sim 0.7$ MW at $n_{e, av} = 3 \times 10^{19} \text{ m}^{-3}$). This scenario is illustrated in Fig. 5 for TCV #57103 (black traces). Even though the gas fueling is negligible, the plasma density is maintained constant by sufficient wall recycling from the carbon wall. The ELMs are monitored with a photodiode measuring the $D_\alpha$ radiation along a vertical line-of-sight. The pedestal profiles are obtained from a recently upgraded Thomson scattering system [10] and fitted with a modified hyperbolic tangent function. Moreover, the profiles have to be shifted such that $T_{e, sep} = 50$ eV (as inferred from the 2-point model) when one wants to compute the peeling-ballooning stability of the pedestal. This scenario has been used to investigate the effect of impurity seeding on the pedestal properties [11, 12].

As seen from the ASDEX-Upgrade experiment reported above, a key ingredient to achieve a small ELM regime is to operate at sufficiently large density at the separatrix ($f_{G, sep} \approx 0.3$) which can be controlled via gas fueling. A mix of type-I and small ELM has been realized in TCV. Indeed, starting from the reference...
type-I ELM regime, a scan in deuterium fueling has been performed on a shot to shot basis. A summary of TCV #57105 for the largest fueling rate is given in Fig. 5 (red traces). As the D₂ flow increases, the following observations can be made (Table 1):

(i) The type-I ELM frequency decreases by a factor of 2 while the relative loss energy ∆W/W remains around 11%;

(ii) The baseline level of the Dα signal increases which might indicate an elevation of the recycling level.

(iii) Small ELMs, in between type-I, are becoming more and more frequent. Their typical frequency is about 2.5 kHz.

A consequence of the reduced type-I ELM frequency is that the plasma density is not controlled anymore and it increases with time, eventually leading to a back transition into L-mode. The lost energy associated with the small ELMs is below 1% which corresponds to the diagnostic resolution. The stored energy is not notably affected since the pedestal temperature is reduced by 15% at the end of the fueling scan while the pedestal density increases by the same amount. The density growth at the pedestal is less rapid than the separatrix density elevation. As a consequence the ratio nₑ,sep/nₑ,ped increases by a factor 2 from 0.25 to 0.5 (Fig. 6(a)). Despite the fact that the wall recycling is increasing, no significant carbon accumulation in the plasma core is observed leading to a reduced fraction of core radiation with gas fueling.

An outward shift of the density pedestal, together with a reduction of the pedestal widths, are observed with increasing fueling (Fig. 6(b)). Both effects are leading to a reduction of the peeling-ballooning stability for type-I ELMs. In addition, for this scenario with low shaping, no evidence of a high density front at the high field side [13] is reported so far from TCV, conversely to AUG. This might be due to the TCV open divertor geometry and will be reassessed once the TCV divertor will be closed with baffles [14].

Finally, since no broadband turbulence has been observed on the magnetic probes, it cannot be concluded if these small ELMs are type-II. Nevertheless, a similar fueling scan for plasmas at higher triangularity, discussed in Ref. [11], also shows a transition to a mixed ELM regime, with, in this case,
Table 1. Summary of fueling scan of type-I ELMy H-mode in TCV with \( q_{95} = 4.5, \delta = 0.4, P_{NB} = 1\text{MW}. \)

<table>
<thead>
<tr>
<th>( \Gamma_{D2} ) (mbarL/s)</th>
<th>( I_{ELM} ) (Hz)</th>
<th>( \Delta W ) (W)</th>
<th>( T_{e,\text{ped}} ) (eV)</th>
<th>( W_{MHD} ) (kJ)</th>
<th>( P_{\text{rad}} ) (kW)</th>
<th>( \Gamma_{rad,\text{core}} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>103±21</td>
<td>11±1</td>
<td>203±12</td>
<td>10±0.2</td>
<td>187±7</td>
<td>34±3</td>
</tr>
<tr>
<td>5</td>
<td>109±29</td>
<td>10±2</td>
<td>144±9</td>
<td>11±0.5</td>
<td>190±13</td>
<td>32±6</td>
</tr>
<tr>
<td>15</td>
<td>96±38</td>
<td>11±3</td>
<td>185±5</td>
<td>10±0.1</td>
<td>230±13</td>
<td>30±4</td>
</tr>
<tr>
<td>28</td>
<td>65±14</td>
<td>12±1</td>
<td>147±7</td>
<td>10±0.1</td>
<td>239±12</td>
<td>31±3</td>
</tr>
</tbody>
</table>

Figure 5. Overview of TCV shots 57103 (\( \Gamma_{D2} = 0 \)) and 57105 (\( \Gamma_{D2} = 28\text{mbarL/s} \)) showing how type-I ELMs are reduced with strong fueling.

3. Small ELM regime accessibility with plasma shaping

3.1. Small ELM regime for plasma with high triangularity in TCV

Type-II and/or grassy ELMs are usually observed at large plasma triangularity [15, 3, 16, 4]. A small ELM regime with controlled plasma density has been achieved in TCV. Two discharges (LSN, \( I_p=170\text{kA}, B_T=1.4\text{T} \)) have been performed with the exact same parameters except the upper triangularity which changes from \( \delta_u=0.1 \) (#61057, \( \delta = 0.4, \Delta_{sep}=24\text{mm} \))
Parameter dependence for small ELM regimes in TCV and AUG

transition giving $f_{G,ped} \simeq 0.35$. For the medium triangularity discharge, the ELMs are large type-I ELMs ($f_{ELM} = 100$ Hz, $\Delta W/W \sim 10\%$) while for the high triangularity discharge, type-I ELMs are fully suppressed and replaced by small high frequency ELMs for which $\Delta W/W < 1\%$.

Later in the discharge, the fuelling was increased by a factor of 8, resulting for the high triangularity case, to an increase of the plasma density up to an H-mode density limit disruption. For the medium triangularity shape, the type-I ELM frequency decreases so the density increases and a back-transition to L-mode is observed.

Although, at low fueling rate, the plasma confinement usually improves when the triangularity is increased [16], here, the stored energy is the same for both triangularities and the density is perfectly well controlled in both situations. In Fig. 8, the temperature and density pedestal profiles are plotted. They are remarkably similar for both discharges even though the kinetic profiles are selected in the [75%-90%] phase of the type-I ELM cycle while they are time averaged for the small ELM case. As a consequence, the pedestal pressure is only increased by less than 5% for the large $\delta$ case. Some plasma and pedestal parameters are compared in Table 2.

An expected benefit of the small ELM regime is a reduction of the steady state target heat loads. For both plasmas, the heat loads at the outer strike point have been estimated with infrared measurement [17]. Figure 9 shows the perpendicular heat flux along the outer divertor as a function of time. Compared to the type-I regime, the peak heat flux is reduced by a factor of about 10 with the small ELM regime, reaching similar levels as the inter-type-I ELM periods. In addition, compared to the value evaluated in between type-I ELMs, the time averaged heat flux decay length $\lambda_q$ for the small ELM case is about 20% larger (6.5 mm vs 5.5 mm) and can be seen as a possible indication of a larger SOL cross-field transport.

In line with JT60-U results [18], when the input power is reduced (1 MW NBI only) the type-I ELMs are not fully suppressed for large $\delta$ and a regime of mixed ELMs is established as for the medium triangularity scenario discussed in Section 2.

3.2. Effect of closeness to double-null on the small ELM regime in AUG

In AUG, the role of the SOL density has been revisited [6]. Indeed, it turns out that a large separatrix density ($f_{G,sep} \sim 0.3$) is not a sufficient condition to achieve the small ELM regime. This has been demonstrated in AUG #34483 (Fig. 10). A small ELM regime is obtained with a constant large gas fueling, in a shape close to DN ($\Delta_{sep} = 7-9$ mm). After $t = 4.0$ s, the plasma

![Figure 7](image-url)
## 4. Physical interpretation

The experimental results from AUG and TCV are consistent within each other and can be summarized as follows: a small ELM regime at high confinement can be achieved \textit{if and only if} two conditions are fulfilled at the same time: the separatrix density is large enough: $f_{G,sep} \geq 0.35$ and the plasma shape is close to a double-null configuration. In the following, the physical implications are discussed, starting with the pedestal stability analysis.

For the AUG and TCV plasmas discussed in Section 3, the pedestal stability is analyzed using CLISTE and MISHKA codes for AUG [13] and CHEASE and KINX for TCV plasmas [19], respectively. The experimental $T_e$ and $n_e$ profiles are fitted with a modified hyperbolic tangent function and shifted such that $T_{e,sep} = 100$ eV for AUG and 50 eV for the TCV cases. The $j - \alpha$ stability diagrams are shown in Fig. 11. Here, $j$ is the current density and $\alpha$ is the normalized pedestal pressure gradient. As expected, for the type-I ELMy cases (low shaping), the experimental pedestal pressure and current are close to the peeling-ballooning stability boundary. When plasmas are strongly shaped towards DN and small ELMs achieved, the intermediate-$n$ peeling-ballooning boundary expands considerably. Nevertheless, the experimental pedestals are still close to this boundary, meaning that the pressure gradient and possibly, the edge current density are increased in both devices when a small ELM regime is achieved.

In addition to the dependence on the separatrix density, the onset of a small ELM regime depends on the closeness to the DN configuration. For both devices, a magnetic equilibrium, taking into account the pedestal bootstrap current self-consistently has
Figure 9. Outer target heat loads measured with IR thermography for a) TCV #61057 (type-I ELMs); b) TCV #61056 (small ELMs); c) Peak heat flux for type-I (black), small (red) and in between type-I ELMs (black; dashed).

Figure 10. Summary of AUG #34483; a) Close look at the magnetic equilibrium around the 2nd X-point xat t=3.5 s (red) and t=5.5 s (black); b) D$_2$ fueling (blue) and vertical position of the magnetic axis (purple); c) divertor shunt current showing that type-I ELMs are progressively restored when the closeness to DN is relaxed.

been computed for type-I and small ELM regimes. The CLISTE code for AUG and the CHEASE code [20] for TCV cases are used, respectively. Figure 12 shows the resulting magnetic shear profile which has been flux surface averaged. It turns out that when the closeness to DN is relaxed, the magnetic shear in the immediate vicinity of the separatrix is larger than for the configuration close to DN. It is also known that ballooning modes with high toroidal mode numbers and driven by the local pressure gradient can be destabilized by a reduced magnetic shear [21, 22]. Therefore, we are conjecturing that small ELMs might be ballooning modes driven unstable in the vicinity of the separatrix. Such modes have high toroidal mode numbers and are therefore radially narrow, driven by the local pressure gradient and stabilized by magnetic shear.

The experimental results from AUG and TCV presented in this paper are in line with our current understanding about the physical mechanism which drives small (either type-II or grassy) ELMs. It can be summarized as follows:

- With strong plasma shaping (short Δ$_{sep}$ and/or
high $\delta$), ballooning modes, driven by the pressure gradient are destabilized in the immediate vicinity of the separatrix where the magnetic shear is locally reduced.

- With strong plasma fueling, large separatrix densities can be achieved and the turbulent transport due to ballooning modes, which increases with density [23], can be large at the separatrix.
- This transport flattens the pressure profile around the separatrix, such that the remaining pedestal width, which determines the stability of the peeling-ballooning modes, becomes narrower. This has a stabilizing influence on type-I ELMs.

5. Conclusions and outlook

This paper reports on joint experiments conducted on AUG and TCV devices in order to assess the effect of plasma fueling and plasma shape on the onset of small ELM regimes (either type-II or grassy). We have clarified the key role of two parameters: the separatrix density and the magnetic shear in the immediate vicinity of the separatrix. In summary, for the onset of a small ELM regime:

- The plasma density at the separatrix must be...
large enough \( \left( n_{e,\text{sep}}/n_G \geq 0.3 \right) \) to drive a large ballooning transport and therefore to flatten the pressure profile near the separatrix, which, finally, stabilizes type-I ELMs.

- The plasma triangularity has to be large enough \( \left( \delta \geq 0.4 \right) \), which in practice, results in a magnetic configuration close to a Double Null (DN), parametrized with \( \Delta_{\text{sep}} \). This leads to a reduction of the magnetic shear in the extreme vicinity of the separatrix. As a consequence, its stabilizing effect on ballooning modes is weakened.

These critical parameters are reported in Table 3 and compared to the ITER expected values [24, 25]. In this paper, it has been demonstrated that the onset of a small ELM regime strongly depends on the separatrix conditions. Therefore, it is important to realize that not only the ITER plasma shape but also the separatrix parameters \( f_{G,\text{sep}} \) and \( \nu_{s,\text{sep}} \) can be matched in nowadays tokamaks. So, a small ELM regime with good confinement might be achievable in ITER. Nevertheless, since it is known that the ITER pedestal collisionality cannot be matched in present machines, a better physical understanding regarding the onset on small ELM regime is needed to gain confidence on a possible extrapolation to ITER and beyond.

As it has been seen, type-I and small ELMs can exist at the same time, suggesting they are excited by different physical mechanisms. The underlying instabilities leading to grassy or type-II ELMs have been hypothesized to be ballooning modes located close to the separatrix, however further experiments devoted to a better understanding of the pedestal and SOL turbulence and particle and heat transport are required. This will be complemented by further development of theoretical models for small/no ELM regimes and by nonlinear MHD simulations using global codes in order to gain confidence in terms of their compatibility with ITER plasmas.

Finally, the effort to understand the physics of small ELM regime will continue under the EUROfusion umbrella with further experiments on AUG, TCV and MAST-U in order to achieve small ELM regime towards \( \eta_{\text{sep}} = 3 \) [26] and ITER-relevant separatrix collisionalities.

### Acknowledgments

This work has been carried out within the framework of the EUROfusion Consortium and received funding from the Euratom research and training programme 2014-2018 and 2019-2022 under Grant Agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission. G. F. Harrer is a fellow of the Friedrich Schiedel Foundation for Energy Technology. This work was supported in part by the Swiss National Science Foundation.

### Appendix A: the EUROfusion MST1 team

Parameter dependence for small ELM regimes in TCV and AUG

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