EXPERIMENTAL CONDITIONS FOR SUPPRESSING EDGE LOCALISED MODES BY MAGNETIC PERTURBATIONS IN ASDEX UPGRADE

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Abstract

Full suppression of Edge Localised Modes (ELMs) by application of an intentional magnetic perturbation (MP) in high-confinement mode (H-mode) plasmas has been achieved in ASDEX Upgrade (AUG) in a shape-match experiment with DIII-D [Nazikian, IAEA FEC 2016]. Recent experiments in AUG aimed to identify critical parameters for accessing ELM suppression. We identify a safety factor window for accessing ELM suppression with $n = 2$ MP ($q_{95} = 3.57 - 3.95$), a maximum plasma edge density ($n_{\text{max}} = 3.3 \times 10^{19}$ m$^{-3}$), but no restriction of the plasma rotation within the range probed so far (boron impurity flow $v_{\text{tor}} = 0 - 40$ km/s). Transitions to and from ELM suppression are initiated by sharp changes of plasma edge density and rotation temporal gradients, which precede the disappearance or reappearance of ELM activity. We investigate the possibility that these changes are caused by a resistive plasma response to the MP, which requires the absence of field shielding induced by cross-field flows at resonant surfaces. Full ELM suppression is obtained in cases with and without zero-crossing of the cross-field electron flow $\omega_{e,\perp}$ at resonant surfaces in the pedestal region, including cases where significant field shielding is expected from two-fluid magnetohydrodynamics (MHD). However, the $E \times B$ flow always crosses zero somewhere in the pedestal region, and particle orbits in resonance with the stationary MP may exist at resonant surfaces. This finding suggests that a kinetic treatment of the plasma response is required to evaluate the shielding of the MP.
1. INTRODUCTION

Full suppression of Edge Localised Modes (ELMs) by application of an intentional magnetic perturbation (MP) in high-confinement mode (H-mode) plasmas has been achieved in ASDEX Upgrade (AUG) in a shape-matching experiment with DIII-D [1, 2]. In contrast to previous H-mode scenarios that retained ELMs with mitigated energy losses in weakly shaped diverted plasmas [3, 4], full ELM suppression in AUG requires stronger shaping of the plasma cross section. This finding has been attributed to larger pedestal plasma pressure, which in turn leads to stronger amplification of the external MP by marginally stable, edge localised, kink-peeling modes [5]. Measurements of the plasma surface displacement [6, 7] in AUG confirm the mode amplification predicted by ideal MHD 3D equilibrium calculations. Different models have been proposed for how the plasma response to an external MP can lead to suppression of ELMs. The inherent non-linearity between displacement and perturbation field in ideal MHD leads to coupling of the MP (with low toroidal mode number, e.g. \( n = 2 \) as in our experiment), with the most unstable ELM modes (typically, \( n \sim 8 - 14 \)) with the effect to produce intermediate-\( n \) modes (\( n = 4, 6, \ldots \)). Non-linear extended MHD simulations using the JOREK code show that this mode coupling can lead to mitigation or even suppression of the ELM crash [8]. Because of toroidicity and elongation and consequently the occurrence of poloidal mode coupling, the ideal edge kink-peeling modes inherently have a pitch-aligned component [9, 10] which can create a resistive response, unless cross-field flows induce helical currents that reduce (“shield”) the resonant MP field at and inside the resonant surface. It has been suggested [11] that the locally enhanced radial transport around resistive resonant layers near the edge gradient region limits the extension of the steep pressure zone and thereby keeps the pedestal stable against peeling-ballooning modes which are believed to be the origin of the ELM crash. Since the resistive response is sensitive to shielding currents this model can be tested by varying cross-field flows that induce these currents. In two-fluid MHD, for example, the relevant cross field flow is that of the electrons, \( v_{e,\perp} \) [12], and it can be tested experimentally whether \( v_{e,\perp} \) needs to be small at a resonant surface near the gradient region for ELM suppression or not.

In this paper, we summarise recent experimental effort in AUG to identify access conditions for ELM suppression. Details of these experiments have been documented in a recent journal paper [13]. Subsequently, we first describe briefly the ELM suppression scenario in AUG and then concentrate on phenomena that might be relevant for ELMing and ELM suppressed H-mode.

2. ELM SUPPRESSION BY MAGNETIC PERTURBATIONS IN ASDEX UPGRADE

The ELM suppression scenario studied mostly so far in AUG uses lower single null with upper triangularity \( \delta_u = 0.22 - 0.26 \), lower triangularity \( \delta_l = 0.4 - 0.5 \) and outer divertor strike point position controlled to be in the optimum pumping position of the AUG solid tungsten divertor III [14]. The variation of \( \delta_l \) originates from Shafranov shift variation as \( \delta_l \) is correlated with \( \beta \) (\( \beta_N = 1.6 - 2.6 \)). Zero or very small (\( \Gamma = 1 \times 10^{21} \) D atoms/s) gas puff is used for low H-mode density. The toroidal field is fixed at \( B_0 = 1.83 \) T for central third harmonic electron cyclotron heating at \( f = 140 \) GHz, in order to maintain a significant electron temperature gradient in the core and thereby avoid accumulation of tungsten impurities in the plasma core. The plasma current is varied between 0.8 and 1.0 MA for an edge safety factor \( q_{95} = 3.4 - 4.0 \).

Time traces of a typical discharge are shown in Fig. 1. After application of the MP with \( n = 2 \), ELMs are first mitigated and then fully suppressed after \( t = 3.0 \) s. Particle losses due to sawtooth crashes are visible in the divertor thermocurrent measurement, but they typically do not trigger ELMs. In addition to main ions, also heavy impurity ions are transported out of the plasma. This is demonstrated by the fast decay of the tungsten (W) concentration and additional radiation caused by two impurity
pulses. The W impurity influx is produced by ICRF pulses with identical phase of all three straps of the new ICRF antennas, instead of an optimum phasing that was predicted and found experimentally to avoid W sputtering [15].

FIG. 2. Operational boundaries of ELM suppression in pedestal \( T_e - n_e \) space (adapted from [13]).

bounding the ELM suppression cases (magenta), which is up to \( \sim 30\% \) below that of unmitigated ELMy H-modes – a harsh penalty for confinement. Reduced MP coil current and/or detuned phasing between upper and lower coils allows to recover partly the pedestal pressure, and so far ELM suppression phases with an H-mode confinement factor of up to \( H_{98P,e,2} \approx 1.1 \) have been obtained. We have not yet observed ELM suppression with a pedestal temperature above \( T_e > 0.95 \) keV (green line) or \( T_i > 1.3 \) keV. Excursions of the pedestal temperature above these values are accompanied with the return of very small ELMs (blue triangles). The pedestal pressure is similar to that found with ELMs mitigated by MP at higher plasma density, demonstrating that avoiding stability limits of small ELMs is an important requirement for ELM suppression.

3. EDGE SAFETY FACTOR CONSTRAINTS

The possible role of resonant surfaces is investigated in ramps of the edge safety factor \( q_{95} \). Figure 3 shows time traces of one such discharge which demonstrates the backtransition from ELM suppression to ELMing H-mode at \( t = 3.6 \) s as an edge safety factor \( q_{95} = 3.95 \) is exceeded for the first time and steady ELM activity resumes after \( t = 3.7 \) s when \( q_{95} \) remains continuously above 3.95. ELM activity is well diagnosed by several measurements, notably inner divertor radiation measured with diode bolometers (second panel) and spikes in the electron cyclotron emission (ECE) in a channel with cold ECE resonance in the scrape-off layer (fourth panel). These spikes are believed to be partly due to downshifted emission from energetic electrons in the confined plasma caused by reconnection events associated with sawtooth and ELM crashes [16]. From this and other discharges, including \( q_{95} \) downward ramps, a reproducible edge safety factor window \( q_{95} = 3.57 \) – 3.91 is identified for which ELM suppression is obtained in AUG in this plasma configuration [13]. A sharp transition occurs at \( t = 3.6 \) s at which the inner divertor bolometer signal drops, and the plasma density begins to rise sharply. Discernible ELM activity starts a few ms later.

FIG. 3. Time traces during backtransition from ELM suppression to ELMing H-mode.
The bottom panel of Fig. 3 shows the toroidal impurity ($B_5^{\pm}$) rotation velocity $v_{\text{tor}}$, measured by charge exchange recombination spectroscopy (CXRS) sightlines which intersects the neutral beam at a poloidal flux $\Psi_n = 0.93$ (pedestal top, at $q = 7/2$) and $\Psi_n = 0.97$ (gradient region, at $q = 8/2$). A sharp change of the rate-of-change of $v_{\text{tor}}$ is detected at the backtransition, $t = 3.6\,\text{s}$ at $\Psi_n = 0.93$. In comparison, at a radius further outward, $\Psi_n = 0.97$, $v_{\text{tor}}$ lags behind by a few ms. The radial positioning of these measurements relative to the edge gradient region is shown in Fig. 4, which shows electron temperature profiles for the shaded time intervals of Fig. 3, i.e. shortly before and somewhat after the backtransition. The figure shows that the radius of the initial rotation change, $\Psi_n = 0.93$, corresponds to the $q = 7/2$ surface, at the pedestal top, while the delayed rotation change occurs at the $q = 8/2$ surface, at the knee of the edge barrier.

4. THE ROLE OF PLASMA ROTATION FOR ELM SUPPRESSION

In ASDEX Upgrade, plasma rotation during ELM suppression can vary significantly and span a similar range of values as in ELM-mitigated H-mode phases [13]. Figure 5 shows the toroidal impurity rotation velocity at flux

![Fig. 4. Edge temperature profiles in ELMy H-mode and ELM suppression.](image)

![Fig. 5. Impurity ($B_5^{\pm}$) rotation at $\Psi_n = 0.8$ vs. peripheral electron density for ELMying and ELM-suppressed H-mode plasmas in ASDEX Upgrade (adapted from [13]).](image)

![Fig. 6. Profiles of angular rotation frequency of impurity ions ($B_5^{\pm}$, left panel), gyrocentres ($E \times B$ flow, middle panel) and electron fluid perpendicular to B ($\omega_{e,\perp}$, right panel) in the edge pedestal region for four selected discharges. Solid curves are calculated with neo-classical $\omega_{B_5^{\pm}}$, dashed curves with $\omega_{B_5^{\pm}} = 0$. The position of various resonant surfaces is marked by vertical dashed lines. (adapted from [13]).](image)
$\psi_n = 0.8$, i.e. well inside the pedestal top. The data set shown contains phases with mitigated ELMs by MP (blue triangles), ELM suppression (magenta circles) and, for reference, one case of unmitigated, large ELMs without MP (red square). The data set is restricted to stationary phases of at least 100 ms duration. In a large range of impurity velocities, $v_{\text{imp}}^{\text{rot}} = 0 - 40$ km/s, both ELM mitigation and ELM suppression are observed. In AUG experiments so far, no threshold in edge rotation or torque input has been observed for accessing or maintaining ELM suppression. It should be noted that in the present experiments only co-Ip directed neutral beams have been used.

For the four cases highlighted in Fig. 5 with coloured triangles of different orientation, Fig. 6 shows profiles of the impurity toroidal rotation (left panel), the $E \times B$ rotation ($\omega_{E \times B}$, middle panel) and the cross-field electron rotation ($\omega_{e,\perp}$, right panel). The latter two quantities, $\omega_{E \times B}$ and $\omega_{e,\perp}$, are derived from the impurity ion and electron force balance equations, as described in Ref. [13]. With the exception of the H-mode edge gradient region, $\psi_n = 0.92 - 1.0$, the ion poloidal flow is small, but contributes to the total fluid rotation and therefore, to $\omega_{E \times B}$ with a strong weight $B_t/B_p$ over the toroidal rotation. Errors of the poloidal flow measurement are amplified as well, which leads to significant errors if the experimental value of $\omega_p^{B5+}$ is used. Therefore we estimate the result by assuming either $\omega_p^{B5+} = 0$ (dashed lines in Fig. 6) or the neoclassical value calculated with the NEOART code [17, 18] (solid lines). For our set of discharges, $|\omega_p^{B5+}|$ from NEOART agreed with the experiment or slightly overestimated it (code result more negative than measured), therefore the two assumptions define a confidence band for $\omega_{E \times B}$ and $\omega_{e,\perp}$. One can see that for some of the cases (shots 33133 and 34214), $\omega_{e,\perp}$ has no zero crossing in the plasma edge region shown ($\psi_n \geq 0.7$). At the $q = 7/2$ surface and outward, the strong electron diamagnetic velocity contribution $\omega_{e,\perp}$ produces large negative electron cross field rotation $\omega_{e,\perp} \leq -10$ km/s which is expected to lead to significant shielding of the resonant plasma response in this region according to fluid models [13]. In contrast, $\omega_{E \times B}$ has a zero-crossing in the edge region for all cases, however at different radii. Within the accuracy of our analysis, it is possible that $\omega_{E \times B} = 0$ is at either the $q = 6/2$ or the $q = 7/2$ surface (depending on the individual case), i.e. we cannot exclude that a kinetic response can influence shielding currents at these surfaces.

5. TRANSITIONS INTO AND OUT OF ELM SUPPRESSION

Despite fuelling, heating mix and MP field are kept constant, very rarely, repetitive spontaneous transitions between ELM suppression and ELMing H-mode can be found. Figure 7 shows time traces of a discharge with three such cycles. During ELM suppression, the plasma density and impurity ion rotation at the pedestal and in the core drop, while in the ELMing phases they recover. Also, the difference between impurity ion rotation at $\psi_n = 0.89$ and $\psi_n = 0.95$ is reduced in suppression phases, i.e. the rotation gradient is reduced between the $q = 6/2$ and $q = 7/2$ surfaces.

At present, we do not know the origin of the spontaneous back-transitions from ELM suppression into ELMing H-mode, which is not normal as most discharges remain continuously in ELM suppression for as long as the required plasma conditions are maintained. One possibility might be the increase of $q_{65}$ towards the boundary of the $q_{65}$ access window during suppression, however in this case, the empirical upper bound $q_{65} = 3.95$ is not quite reached.

However, we can make a few interesting observations from Fig. 7: (a) During ELM suppression, plasma and impurity rotation ($\omega_{B5+}^{\text{imp}}$) are positive (in direction of the plasma current) but decrease slowly from their initial value at the end of the

FIG. 7. A discharge with repeated (“dithering”) transition between ELMy and ELM-suppressed H-mode.
preceding ELMing phase. This implies that \( \omega_{e\perp} \) (not shown in the figure) becomes more negative. (b) In contrast, at the onset of ELMing phases, \( v_{B5+} \) in the gradient region, \( \Psi_n = 0.95 \), reverses sign, i.e. the impurity flow is in the direction opposite to the plasma current, before the flow at all radii accelerates into the ion direction. (c) Plasma edge density and pedestal top plasma rotation are well correlated, both in ELMing and ELM-suppressed phases. (d) The rotation change and transition from ELMing to ELM suppression do not necessarily coincide, as seen at \( t = 4.845 \) s where the plasma starts to spin down, while ELM activity ceases only at \( t = 4.873 \) s.

We can speculate that the distinctly different phases of increasing and decreasing flow are due to different types of torque exerted by the MP onto the plasma edge. Strong braking towards zero rotation and flattening of the rotation profile near rational surfaces are consistent with a resonant plasma response to the MP, while the reversal of the rotation direction may be indicative of approaching intrinsic rotation associated with neoclassical toroidal viscosity (NTV). NTV torque is usually much weaker than resonant torque and would be noted only in the absence of the latter. Transitions into and out of resonant field penetration have been observed in the DIII-D tokamak [19]. In view of our result, item (d) above, penetration of the resonant field by itself is not sufficient for ELM suppression, maybe because small ELMs are destabilised at sufficiently large pedestal pressure gradient and width, regardless of reduced plasma flows.

In ASDEX Upgrade, enhanced fluctuations with a toroidally varying amplitude have been observed during ELM suppression [20] which resemble a similar observation in DIII-D [21]. Figure 8 shows time traces of the initial transition from purely ELMing behaviour (until \( t = 2.61 \) s) to complete ELM suppression (from \( t = 2.68 \) s) in AUG discharge 34548. The \( n = 2 \) MP field (not shown) is applied continuously with optimum phasing, and the gas puff (not shown) is low (\( \Gamma = 1 \times 10^{21} \) D/s) during the entire time interval shown in the figure. The density fluctuations at the plasma midplane correspond to fluctuating transport, which appears as a wide-band spectrum in diode bolometer measurements in the divertor. A spectrogram of a channel viewing the strike zone at the high-field side is shown in the top panel of the Fig. 8, and the total fluctuation amplitude in the second panel. The ELMing phase is characterised by clear intermittency of the signal, while during full ELM suppression, a wide-band turbulence spectrum with more stationary amplitude is observed. During the time interval in between \( (t = 2.61 - 2.68 \) s), this broad-band signal is interspersed with a few small ELMs. It is during this intermediate phase that edge density, temperature, and edge rotation undergo their fastest changes. The onset of the broad-band mode on one hand and the final disappearance of ELMs on the other hand do not exactly coincide, therefore we may conclude that both phenomena have different existence conditions.
6. SUMMARY AND DISCUSSION

Full suppression of ELMs is reliably obtained in ASDEX Upgrade using \( n = 2 \) magnetic perturbations (MP) in H-mode discharges at low density (pedestal plasma density \( n_{\text{ped}} \leq 3.3 \times 10^{19} \text{ m}^{-3} \)). There is a clear sensitivity to the edge safety factor \( q_{95} \), as so far one window for access to ELM suppression has been found in AUG at \( q_{95} = 3.57 - 3.95 \). This finding is consistent with similar \( q_{95} \)-windows found previously in DIII-D for \( n = 2 \) [9] and \( n = 3 \) MP[22] and hints at the possible relevance of the position of rational surfaces that are resonant with the MP. The observation of transitions between states of strong torque towards zero fluid rotation and weak torque towards electron drift-directed mass flow suggests the presence and absence of resonant \((j \times B)\)-torque, respectively, which would be indicative of a resistive plasma response to the MP (“field penetration”) as has been reported for DIII-D [19].

However, our data challenges in various ways a recent model for ELM suppression at DIII-D [11], which predicts a narrow rotation window for which \( \omega_{e,\perp} = 0 \) at a rational surface near the edge gradient region to allow a resistive response to block the edge barrier expansion towards ELM destabilisation:

1. In our experiment, we observe ELM suppression in a wide range of \( \omega_{e,\perp} \) which includes cases with significant \( \omega_{e,\perp} \) rotation at the edge barrier top. The condition \( \omega_{e,\perp} = 0 \) for field penetration arises from two-fluid MHD and has been nicely demonstrated in a seminal experiment using TEXTOR-DED L-mode discharges [23]. However, kinetic modelling [24] shows the existence of additional rotation windows at \( \omega_{E\times,B} = 0 \) for plasma response currents and radial transport. Experimentally, the condition \( \omega_{E\times,B} = 0 \) is practically always accessible somewhere at the edge of H-mode plasmas with co-current rotation due to NBI torque injection (so that \( \omega_{E\times,B} > 0 \) in the plasma core) and \( \omega_{E\times,B} < 0 \) as an essential feature inside the H-mode barrier. In our experiment, \( \omega_{E\times,B} = 0 \) in the vicinity of the \( q = 6/2 \) or \( q = 7/2 \) surfaces.

2. The onset of the rotation change at the transitions between states of low and high torque can be delayed at certain radii, and one can assume that this delay occurs because of viscous momentum transport from the radius of the torque source to the observation radius. In our backtransition experiment at the upper \( q_{95} \)-window boundary described in section 3, the rotation change occurs initially near the \( q = 7/2 \) surface and is reaching the \( q = 8/2 \) surface near the pedestal top only with a delay. The plasma density begins to rise precisely at the time of the response onset at \( q = 7/2 \), indicating a change of transport. However, the temperature and density gradients are flat at this radius before and after this transition, and so it is difficult to see how ELM stability is affected.

3. As shown in Fig. 7, \( t = 4.845 \) s, and Fig. 8, \( t = 2.61 - 2.68 \) s, the transition to the state with strong braking torque and enhanced radial transport is not necessarily inducing ELM suppression immediately. In these cases, ELM disappear only after the plasma density and temperature have already decreased sufficiently. Our experimental results show that the change of transport and the actual transition into persistent ELM suppression can be well decoupled in time. Also, the momentum source seems to be radially separated from the edge gradient region corner which is believed to govern ELM stability. This suggests a more indirect link between transport modifications due to MP penetration and ELM suppression. Additional transport may arise from non-classical radial flows enhanced by resonances of particle orbits with the MP as proposed in Ref. [24] and/or from saturated turbulence as observed, e.g. in DIII-D [21] and ASDEX Upgrade [20]. Transport due to such a saturated mode might well clamp the edge pressure gradient in the absence of ELMs, and only when it is absent then ELM stability takes over to regulate pedestal profiles. The precise nature of the interplay of transport enhancement and ELM stability will have to be studied further in new experiments in ASDEX Upgrade and other machines.

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