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Experimental conditions for suppressing Edge Localised Modes in ASDEX Upgrade

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Motivation

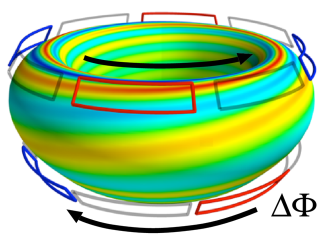
Full suppression of Edge Localised Modes has been achieved in ASDEX Upgrade (AUG) in a shape matching experiment with DIII-D [R Nazikian, IAEA 2016, post-deadline paper].
The "trick" was to increase plasma triangularity and thereby pedestal pressure.
The phenomenology of ELM suppression in AUG is similar to that in other machines (DIII-D, KSTAR, EAST). We summarise here experiments in AUG during 2016 and 2017 which aim to explore critical parameters for accessing ELM suppression with the main goals of identifying the physics mechanisms and give indications for performance optimisation.

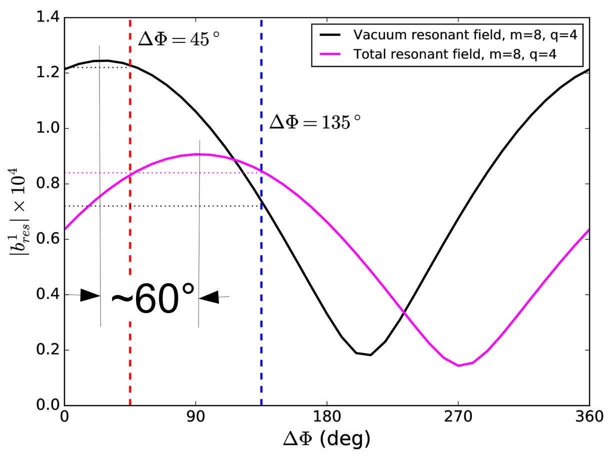
1. Magnetic Perturbation

Different mechanisms for the interaction of the magnetic perturbation (MP) with the plasma can be distinguished by their poloidal spectrum (m: poloidal mode number)

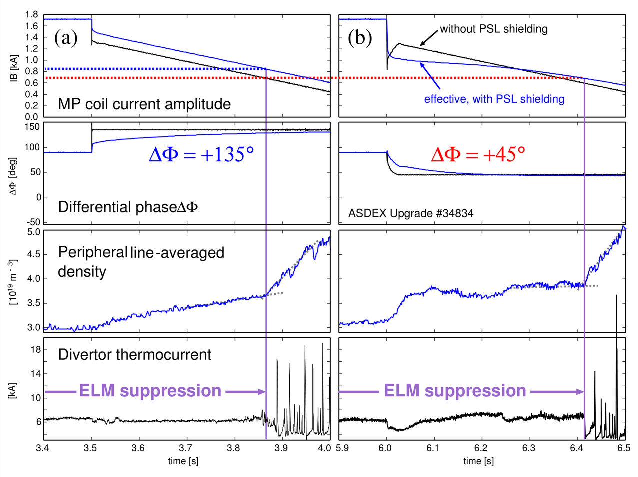
Magnetic field-aligned (resonant) perturbation: m = q.n
Maximum plasma response: m = q.n + Δm
n: toroidal mode number, here: n=2 q: safety factor

Phase shift ΔΦ between currents in two rings of MP coils is used to vary the amplitude of the resonant MP component.





MARS-F calculations [1] predict that MP is amplified by "kink-peeling" plasma response leading to a shift of optimum ΔΦ by ~60° (magenta curve) w.r.t field alignment (black curve).
The amplification is confirmed by measurements of the helical plasma deformation [2].



Here, we measure the MP coil current threshold for the back-transition from ELM suppression for two phasings, ΔΦ=45° and 135°. The measured threshold values are very similar, demonstrating that the plasma response is important for ELM suppression.

[1] D A Ryan et al, Plasma Phys. Control. Fus. **57** (2015) 095008
[2] M Willensdorfer et al., Plasma Phys. Control. Fus. **58** (2016) 114004, Nucl. Fusion **57** (2017) 116047

Summary and Conclusions

Main access conditions for ELM suppression in ASDEX Upgrade are:

1. Magnetic perturbation that couples to least stable edge kink-peeling modes (optimum field amplification)

2. Edge safety factor within a window q95=3.57-3.95
More windows at lower and higher q95 might exist but have not yet been explored.

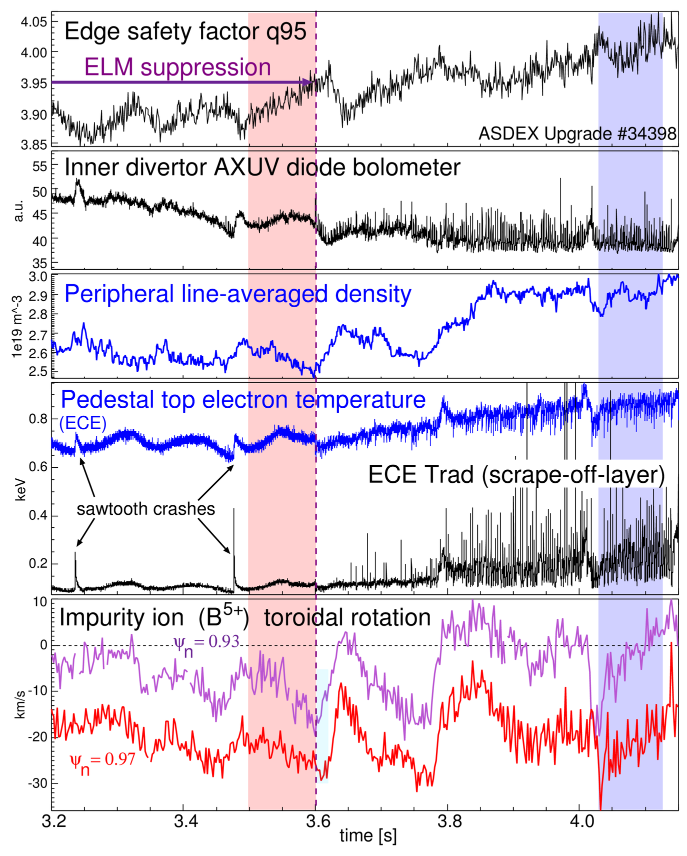
3. Low edge density $n_{e,ped} < 3.3\ 10^{19}\ m^{-3}$. The nature of this limit is not yet fully clear:
- (Small) ELMs return at higher pedestal pressure and similar pedestal temperature, i.e. higher pedestal density.
- Not obviously a collisionality limit, as we have no cases with ELMs at higher collisionality and the same density.

4. No apparent limit in plasma rotation found as yet.
- So far, we have used co-NBI with varying beam geometry. (no ctr-NBI)
- We find ELM suppression with significant cross-field electron flow at rational surfaces.
- A resistive response is possible for radii at which particle orbits are resonant with the MP (zero ExB flow)

Transitions to/from ELM suppression are sharp, sometimes repetitive, and initiated by a transport change in the pedestal top region. Strong braking torque is seen during ELM suppression, suggestive of field penetration and consequential jxB torque.

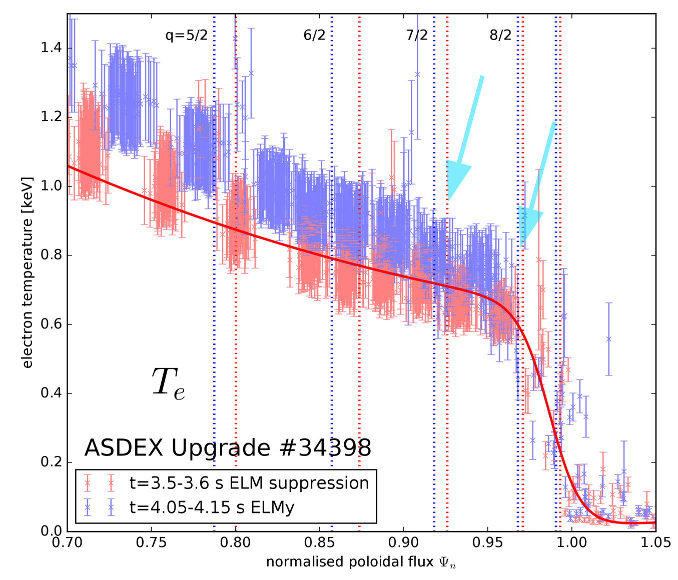
2. Safety factor within a window

A dependence of ELM suppression access on edge safety factor has been reported for DIII-D MP with n=3 [3] and n=2 [4]. We ramp q95 in the range 3.2-4 by variation of the plasma current at fixed toroidal field and find ELM suppression reproducibly in the range q95 = 3.57-3.95.



Shown here is a back-transition (at t=3.6 s) from ELM suppression to (mitigated) ELMs, which occurs as q95 rises above 3.95.

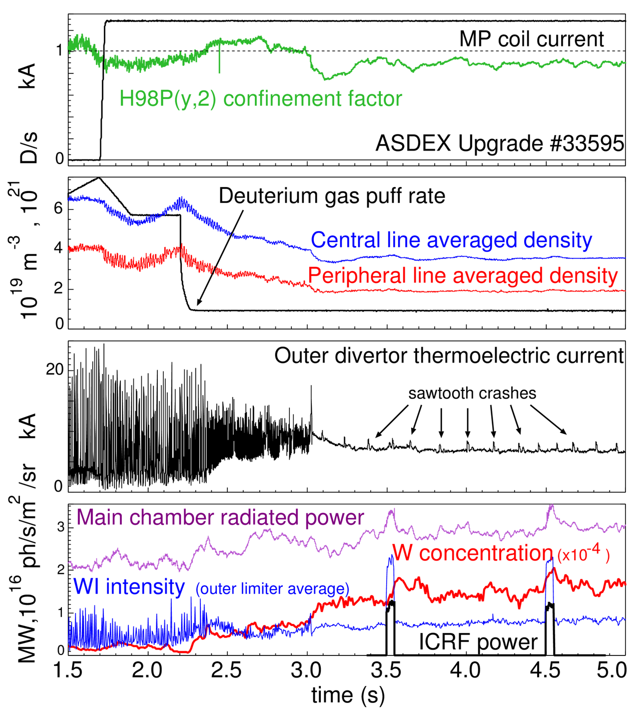
The transition is sharp and begins with a sudden change of the change rates of edge density and plasma rotation. A small time delay at ψ_n=0.93 (pedestal top) compared to ψ_n=0.97 (pedestal knee) indicates that there is a change of momentum input on the pedestal top.



Rational surfaces m/n=7/2, 8/2 are near Ψ_n=0.93 and ψ_n=0.97, repectively. The existence of q95 windows raises the question whether a resonant response is essential.

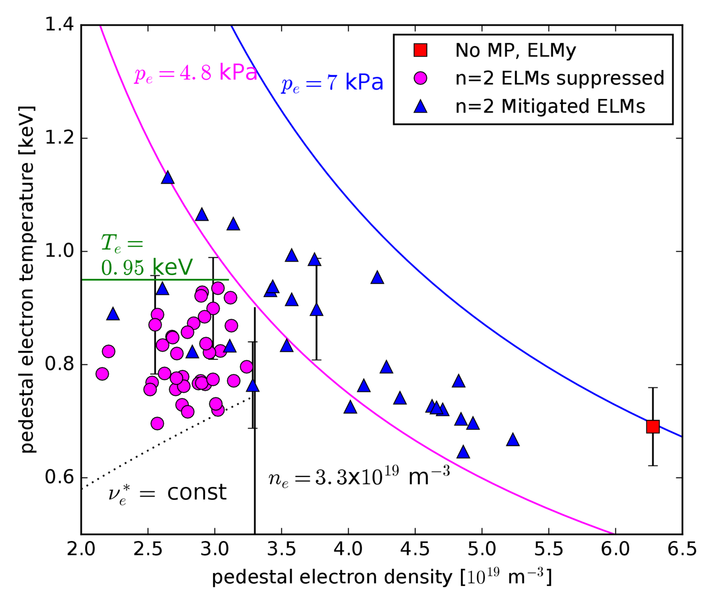
[3] M E Fenstermacher et al, Phys. Plasmas 15 (2008) 056122
O Schmitz et al, Nucl. Fusion 52 (2012) 043005
[4] M J Lanctot et al, Nucl. Fusion 53 (2013) 083019

3. Low Edge Density



The figure shows time traces of the startup of an ELM suppression experiment:
1. Application of MP coil current at high density causes moderate ELM mitigation.
2. After gas puff is reduced, the density drops and ELMs become smaller
3. The transition to full ELM suppression occurs at t=3.0 s, followed by a further density reduction.

Heavy impurities are transported out of the plasma during ELM suppression. Tungsten (W) is injected by sputtering from W-coated ICRF limiters during two pulses with "bad" antenna strap phasing. (Normally, phasing is optimised to suppress W sputtering [5]. The W concentration in the plasma decays quickly.



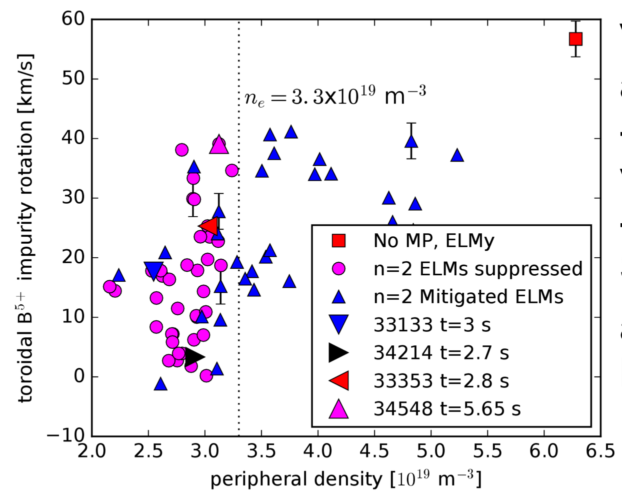
The left figure shows the Te-ne edge operational space for ELM suppressed (magenta), mitigated ELMing (blue) and one case of type-I ELMs (red square).

ELM suppression is obtained only for low edge density, $n_{e,ped} < 3.3\ 10^{19}\ m^{-3}$

At present, we cannot distinguish this from a collisionality boundary – there are no ELMing cases with higher collisionality but same density below this limit.
However, mitigated ELMs decorate a constant pressure line, with all ELM suppression cases below this pressure. One can conjecture that ELM instability must be avoided for suppression.

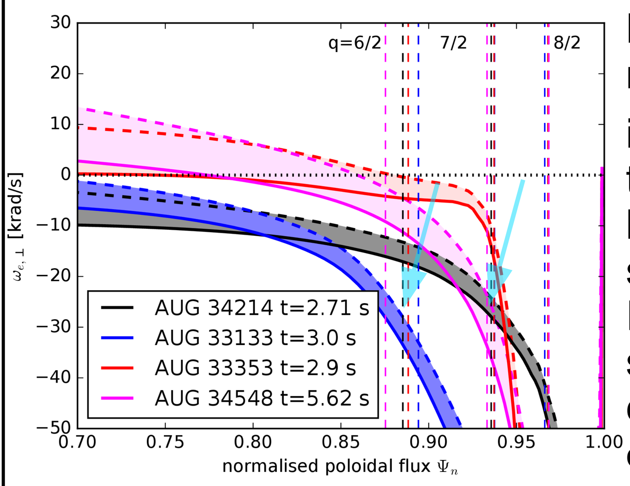
[5] V Bobkov et al, Nucl. Fusion 56 (2016) 84001

4. No threshold in plasma rotation

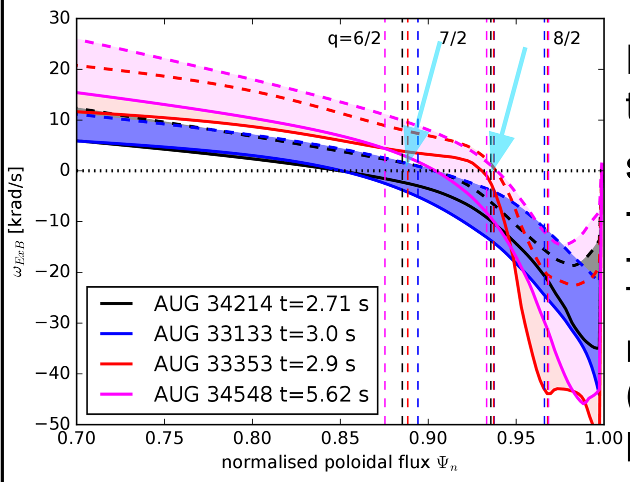


Variations of plasma rotation are produced by:
- NBI torque (mostly radial vs. tangential co-Ip beams)
- Plasma density
So far, no v_{tor} restrictions for accessing ELM suppression have been found.

In 2-fluid MHD models [6], the electron cross-field rotation $\omega_{e,\perp}$ induces helical currents that can shield the resonant MP plasma response. If the RMP is important, then access to ELM suppression should be possible only if $\omega_{e,\perp}$ =0 near a resonant surface where q=m/n (m: any integer).



Moreover, according to a recent model [7], $\omega_{e,\perp}$=0 is required near the knee of the edge gradient region to block its expansion and suppress ELMs.
In AUG, we find ELM suppression as well in cases with significant $\omega_{e,\perp}\neq0$ near and in the edge gradient region.

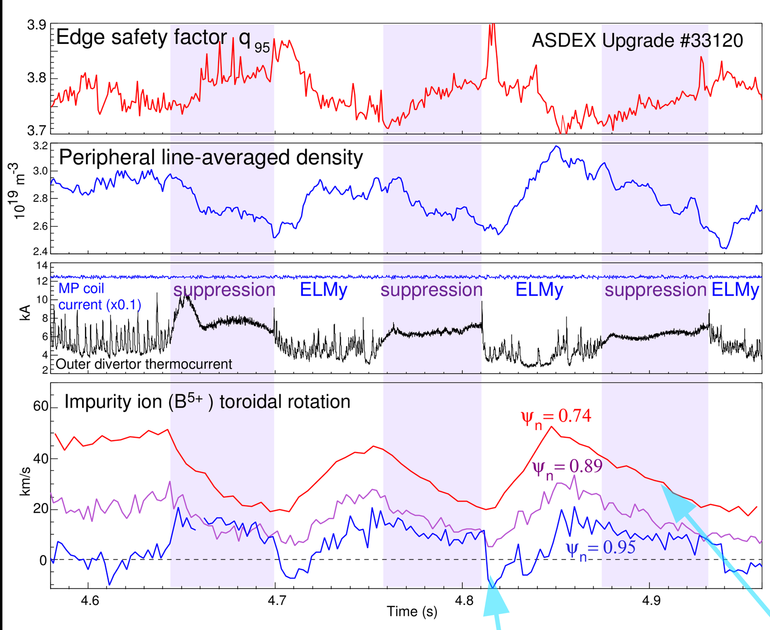


However, in our experiments there is always a ω_{ExB}=0 surface near the edge:
- co-Ip NBI torque in the core
- negative Er well at the edge
The RMP shielding current might be influenced (reduced) there by (trapped) particle redistribution.

A kinetic model [8] demonstrates the existence of a "kinetic" plasma response at ω_{ExB} with significant MP and radial particle transport.

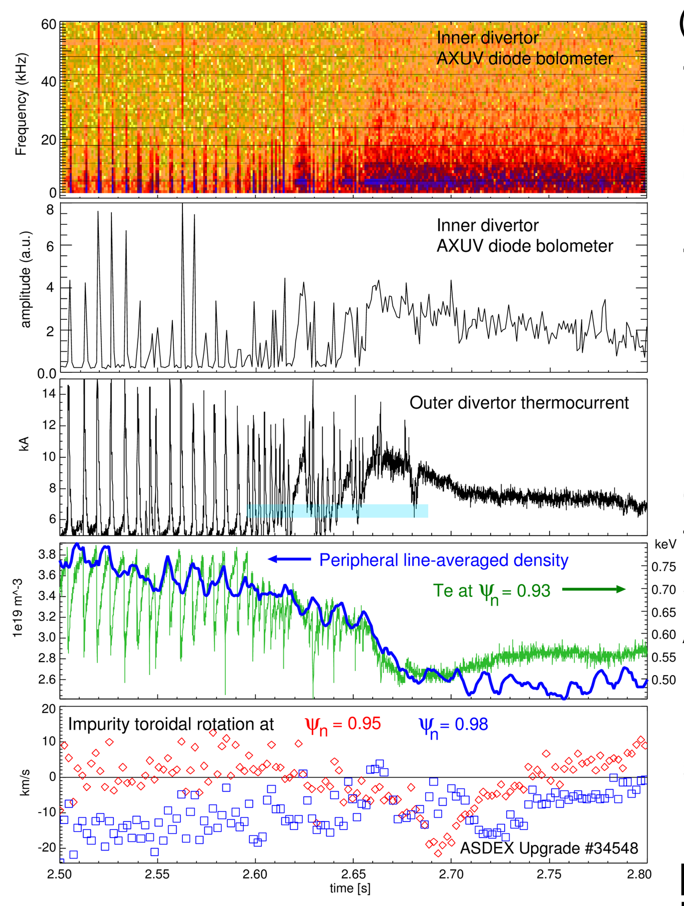
[6] M Bécoulet et al, Nucl. Fusion 52 (2012) 54003
[7] M Wade et al, Nucl. Fusion 55 (2015) 23002
R A Moyer et al, Phys. Plasmas 24 (2017) 102501
[8] M F Heyn et al, Nucl. Fusion 54 (2014) 64005

Transitions into/out of suppression



Occasionally, repetitive, "dithering" transitions into and out of ELM suppression can be found in AUG.
The reason is yet unknown, possibly it is caused by the q95 variation near the upper limit.

The transitions are accompanied with direction changes of the toroidal flow rate-of change, with a) strong braking during ELM suppression towards zero (resonant jxB torque?) and b) brief phases with counter-Ip rotation as ELMs resume (non-resonant NTV torque?)



The transition is also characterised by a change of transport mechanism.
The example on the left is a forward transition.
From t=2.6-2.7 s, the plasma switches between ELMing state and a state of more broadband fluctuations of fluxes, as seen in the inner divertor AXUV diode bolometer.
During suppression, a broadband mode is also seen in midplane reflectometry [9].

[9] N Leuthold et al, EPS Conf Plasma Phys 2018, P1.1109

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EUROfusion

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