Loss of ELM suppression with non-axisymmetric magnetic perturbations in ASDEX Upgrade helium plasmas

W. Suttrop[1], O. Grover[1], N. Leuthold[2], M. Markl[3], R. M. McDermott[1], A. Kappatou[1],
D. A. Ryan[4], E. Viezzer[1,5], M. Willensdorfer[1] and the ASDEX Upgrade Team*
[1]*Max-Planck-Institut für Plasmaphysik, D-85740 Garching, Germany,*
[2]*Columbia University, New York, U.S.A.,*
[2]*CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, U.K.,*
[3]*Fusion@ÖAW, Institute for Theoretical Physics, TU Graz, Austria,*
[4]*University of Seville, Seville, Spain*

We examine the possibility to suppress Edge Localised Modes (ELMs) with Resonant Magnetic Perturbations (RMP) in the ASDEX Upgrade (AUG) tokamak during the gradual transition from pure deuterium (D) to pure helium (He) plasmas. This study is motivated by the initially envisaged possibility for ITER to use He plasmas during its initial, pre-nuclear operation phase and rehearse RMP ELM control early on in the ITER life cycle.

For our experiment we use a proven scenario in AUG that has allowed for years to access RMP ELM suppression reliably in deuterium plasmas [1]: plasma current $I_p = 0.9$ MA, toroidal field $B_t = -1.835$ T for central deposition of electron cyclotron resonant heating (ECRH) in the 3rd harmonic. Plasmas are heated by $P_{\mathrm{NBI}} = 5.9$ MW deuterium neutral beam injection and $P_{\mathrm{ECRH}} = 2.3$ MW ECRH power.

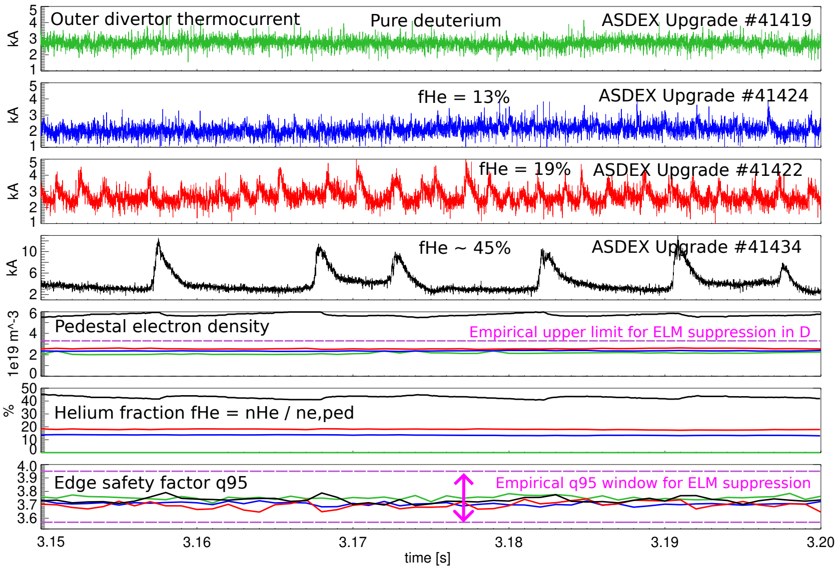

Figure 1: *Time traces of pulses with varying helium concentration.*

After a reference discharge in pure deuterium, part of the initial deuterium gas fuelling is replaced with helium, resulting in a moderate helium concentration which is varied from pulse to pulse. Figure 1 shows time traces of the most interesting discharges with He fractions of $f_{\mathrm{He}} \equiv n_{\mathrm{He}}/n_{\mathrm{e,ped}} \sim 0\%, 13\%, 19\%,$ and 45%.

For all plasmas, RMP with toroidal mode number $n = 2$ and optimum phasing for resonant coupling is applied. The safety factor in all cases is

---

*See author list of U. Stroth et al, Nucl. Fusion **62** (2022) 042006

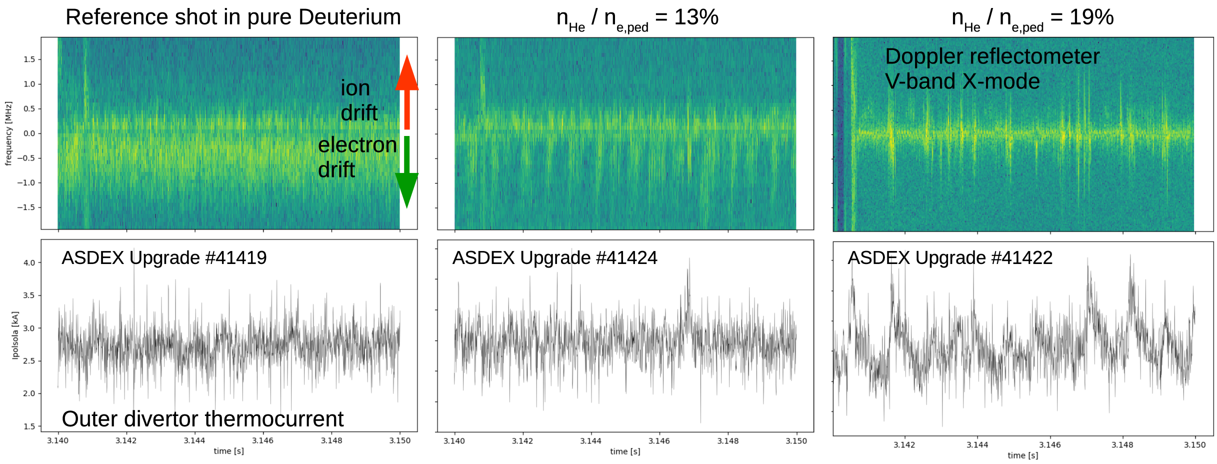

Figure 2: *Spectrograms of Doppler reflectometer measurements in the edge gradient region for* $f_{\mathrm{He}} = 0, 13\%$ *and* 19%.

well within the documented window $q_{95} = 3.57 - 3.95$ for ELM suppression access [1]. Except for the highest He fraction, the edge pedestal density is kept below the empirical limit for ELM suppression, $n_{\mathrm{e,ped}}^{\mathrm{max}} = 3.3 \times 10^{19}$ m^{-3}. For $f_{\mathrm{He}} \leq 13\%$, ELMs are fully suppressed. At $f_{\mathrm{He}} \sim 19\%$, individual ELM crashes are detected, as shown here by the outer divertor thermocurrent. At high He concentration ($f_{\mathrm{He}} \sim 45\%$), the thermocurrent excursions increase and the ELM repetition frequency decreases.

During full ELM suppression, characteristic edge turbulence is observed, which causes particle transport across the H-mode barrier region [2]. Figure 2 shows Doppler reflectometer measurements for the first three cases discussed above, illustrating the changes of edge density fluctuations with increasing He concentration. The probe frequency is tuned to the edge gradient region in X-mode. In the pure deuterium plasma, continuous turbulent activity is found, as described in Ref. [2]. The spectrum is broad and asymmetric, with its maximum amplitude in the electron drift direction (in the laboratory frame). The divertor thermocurrent is noisy, but no ELM-like spikes are observed. At $f_{\mathrm{He}} = 13\%$, while ELMs are still suppressed, the edge fluctuations become intermittent, but only occasionally, bursty excursions are seen in the divertor thermocurrent. At $f_{\mathrm{He}} = 19\%$, the fluctuations are typical, distinct ELM bursts with sub-millisecond duration and symmetric spectrum, which are correlated with peaks in the divertor thermocurrent signal.

Edge profiles of electron temperature T_e and density n_e (from integrated data analysis, IDA [3]) as well as ion temperature T_i and toroidal rotation ω_{tor} (from charge exchange recombination spectroscopy, CXRS, on B^{5+} trace impurities) are compared in Fig. 3 for the ELM suppressed plasmas with $f_{\mathrm{He}} = 0\%$ and 13% and the case with ELMs returning at $f_{\mathrm{He}} = 19\%$. The profiles of T_e, T_i and ω_{tor} are virtually identical for $f_{\mathrm{He}} = 13\%$ and $f_{\mathrm{He}} = 19\%$. T_i and ω_{tor} are higher with He seeding than in pure D, but in both cases with He in the range where ELM suppression in pure D can be obtained [1]. The electron density is somewhat higher at $f_{\mathrm{He}} = 19\%$ than at $f_{\mathrm{He}} = 13\%$. The density difference is fairly small in view of the different He levels and

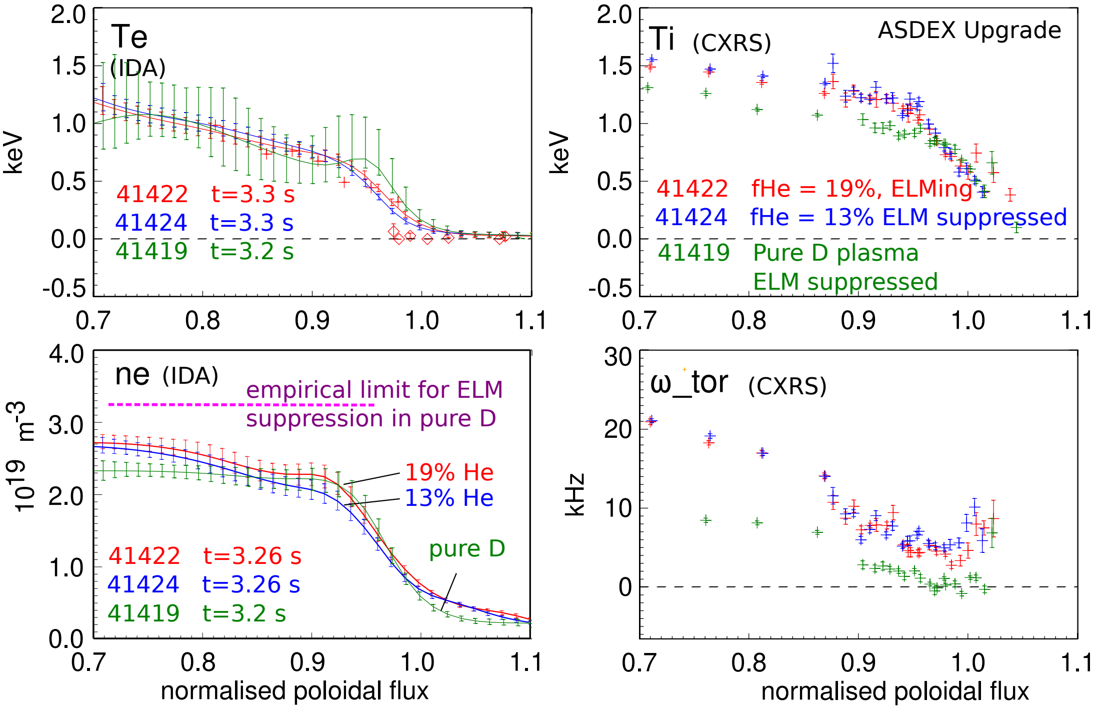

Figure 3: *Edge profiles of* n_e, T_e, T_i *and toroidal rotation* ω_{tor}

therefore different fuelling and different types of particle losses (turbulent or ELM-related) in the three plasmas.

In summary, we find that the addition of moderate fractions of helium, $f_{\text{He}} \equiv n_{\text{He}}/n_{\text{e,ped}} \geq 19\%$, leads to the return of ELMs despite all known requirements for ELM suppression (in deuterium plasmas [1]) being met. The search for the underlying reason is complicated by the fact that the physics of RMP ELM suppression is not yet fully understood.

One can argue that in order to expect similar plasma behaviour one should match dimensionless quantities (e.g. ρ^*, ν^*, β) rather than physical edge parameters (T_e, n_e, T_i, ω_{tor}). However, the edge parameter boundaries for ELM suppression are empirically best described by a maximum edge density [1]. In fact, n_e is the only parameter that changes as the He fraction is increased from $f_{\text{He}} = 13\%$ (suppression) to $f_{\text{He}} = 19\%$ (ELMing). Strangely, ELM suppression is lost at $n_{\text{e,ped}} \approx 2.5 \times 10^{19}$ m^{-3}, well below the empirical limit in pure D ($n_{\text{e,ped}} \sim 3.3 \times 10^{19}$ m^{-3}).

The close similarity of the edge parameters (Fig. 3) for the marginally ELM suppressed and ELMing cases might suggest that the return of ELMs is caused by the explicit presence of helium in the plasma and not by the minor variations of the edge profiles. RMP penetration onto rational flux surfaces is widely believed to be essential for ELM suppression. In fluid models, the bifurcation towards a resistive plasma response is mainly governed by the electron fluid, while the ion species enters indirectly via the ion (mass) velocity and ion diamagnetic rotation. First calculations using the kinetic model presented in Ref. [5] find a correlation of RMP penetration with the transition to ELM suppression in AUG deuterium plasmas, and predict unchanged plasma response if deuterium is exchanged with helium, while experimentally, helium plasmas remain ELMing.

We also note that in our He concentration scan ELMs return at ∇n_e, ∇p_e below that for pure deuterium plasmas. In presence of non-axisymmetric magnetic perturbations the initial growth of ELM precursor modes restricts itself to a helical region with reduced magnetic shear (field line torsion) which first becomes unstable against ideal ballooning as the pressure gradient recovers in between ELMs [4]. It is conceivable that this unfavourable shear region reduces the overall critical pressure gradient for destabilisation of ELMs compared to the axisymmetric case. However, the ballooning stability boundary does not explicitly depend on ion mass. Simply swapping out D with He ions reduces the ion number density and hence the total pressure at same T_e, T_i and n_e, making a plasma more stable against ballooning while experimentally, ELMs are observed in the He and not the D plasmas. The ion charge and ion density can enter via the edge bootstrap current density, which controls the magnetic shear and therefore edge stability. This will have to be evaluated. Stability calculations for coupled peeling-ballooning modes in helically deformed plasmas are in progress [6], but have not yet been applied to ELM suppressed plasmas.

Finally, the role of the edge turbulence for the suppression of ELMs remains elusive. The intermittency of the observed mode activity at $f_{\mathrm{He}} \sim 13\%$ may indicate that the drive for the underlying instability weakens as He is added. In case of a pressure gradient-driven instability, this might be explained by the reduced total pressure due to ion dilution. Surprisingly, this happens very close to the He concentration at which ELMs return ($f_{\mathrm{He}} \sim 19\%$) and at a very similar pressure profile. If this is not a pure coincidence, it may suggest a subtle relation between the continuous broadband turbulence and the ELM instability, which hopefully can be clarified by future experimental and modelling efforts.

References

[1] W Suttrop *et al*, Nucl. Fusion **58** (2018) 096031
[2] N Leuthold *et al*, Nucl. Fusion **63** (2023) 046014
[3] R Fischer *et al*, Fus. Science Tech. **58** (2010) 675
[4] M Willensdorfer *et al*, Phys. Rev. Lett. **119** (2017) 085002;
Plasma Phys. Contr. Fus. **61** (2019) 14019; T Cote *et al*, Nucl. Fus. **59** (2019) 16015
[5] M Markl *et al*, *this conference*; subm. Nucl. Fus.
[6] J Puchmayr *et al*, *this conference*; accepted for Nucl. Fus., doi 10.1088/1741-4326/acdd12

Acknowledgement: This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052-200 – EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

M. Markl gratefully acknowledges funding from the Friedrich Schiedel Foundation for Energy Technology.