Full suppression of Edge Localised Modes with non-axisymmetric magnetic perturbations at low plasma edge collisionality in ASDEX Upgrade

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Full suppression of Edge Localised Modes (ELMs) by small non-axisymmetric magnetic perturbations (MP) of high-confinement-mode (H-mode) plasmas is one of the most promising techniques for ITER to avoid excessive erosion of the first wall due to the impulsive energy losses induced by ELMs. However, few experiments have so far reproduced the DIII-D ELM suppression scenario [1] and full ELM suppression has long been searched for in ASDEX Upgrade (AUG) [2]. Previous experiments in AUG were performed at low triangularity, however, a recent AUG/DIII-D similarity experiment [3] has shown that it is important to increase the triangularity in order to achieve full ELM suppression in AUG [4]. The observation of an increased edge pressure gradient at elevated triangularity [3] suggests stronger amplification of the externally applied MP by marginally stable kink-peeling modes [5] as a possible origin of the plasma shape dependence.

ASDEX Upgrade is equipped with two rows of in-vessel MP saddle coils, consisting of eight coils each which are equally spaced in toroidal direction. These rows are poloidally located above and below the outer midplane. Adjustment of the phase difference between upper and lower coil row (“differential phase” $\Delta\Phi$) allows the coupling of the MP to be controlled such as to amplify plasma modes driven by the H-mode edge pressure gradient [5]. In the present experiment, MPs with toroidal mode number $|n| = 2$ and $\Delta\Phi = 90^\circ$ are applied throughout, as found appropriate for the plasma configuration used ($B_t = -1.83$ T, $I_p = 0.885 - 0.95$ MA, $q_{95} = 3.9 - 3.7$). Plasmas are heated with 6 MW neutral beam (NB) power (fully co-I_p injected) and up to 2.4 MW electron cyclotron heating power (ECRH) at 140 GHz, absorbed centrally at the third harmonic (X3). Strong central heating is the main tool to preserve strongly peaked temperature profiles and prevent accumulation of heavy impurities which can enter into the plasma by sputtering from the all-metal wall of AUG.

The main properties of the ELM suppression scenario are illustrated in Fig. 1 which shows time traces of discharge 34214 that demonstrates complete suppression of ELMs for almost the entire flat top duration. The discharge is started up in ELMy H-mode, albeit with MP on to avoid large, low frequency ELMs. At $t = 2.2$ s, the gas puff is cut to a small value of 1×10^{21} D/s. ELMs become fully suppressed as the pedestal collisionally drops below $\nu^*_{\rm ped} = 0.3$ at $t = 2.6$ s and no ELMs occur until the plasma current is ramped down at $t = 7.2$ s. The absence of ELM crashes can be seen in many different diagnostics, including the outer divertor thermoelectric current. Reasonably stationary conditions are reached, with the total radiated power $P_{\rm rad} \leq 4$ MW, indicating that no significant impurity accumulation occurs.

During the long ELM-suppressed phase, the heating scheme and MP coil current are varied. Before $t = 3.1$ s and after $t = 4.6$ s, the two most tangential NB sources (tangential at about half radius on the high field side) and one more radially injecting source are used. In

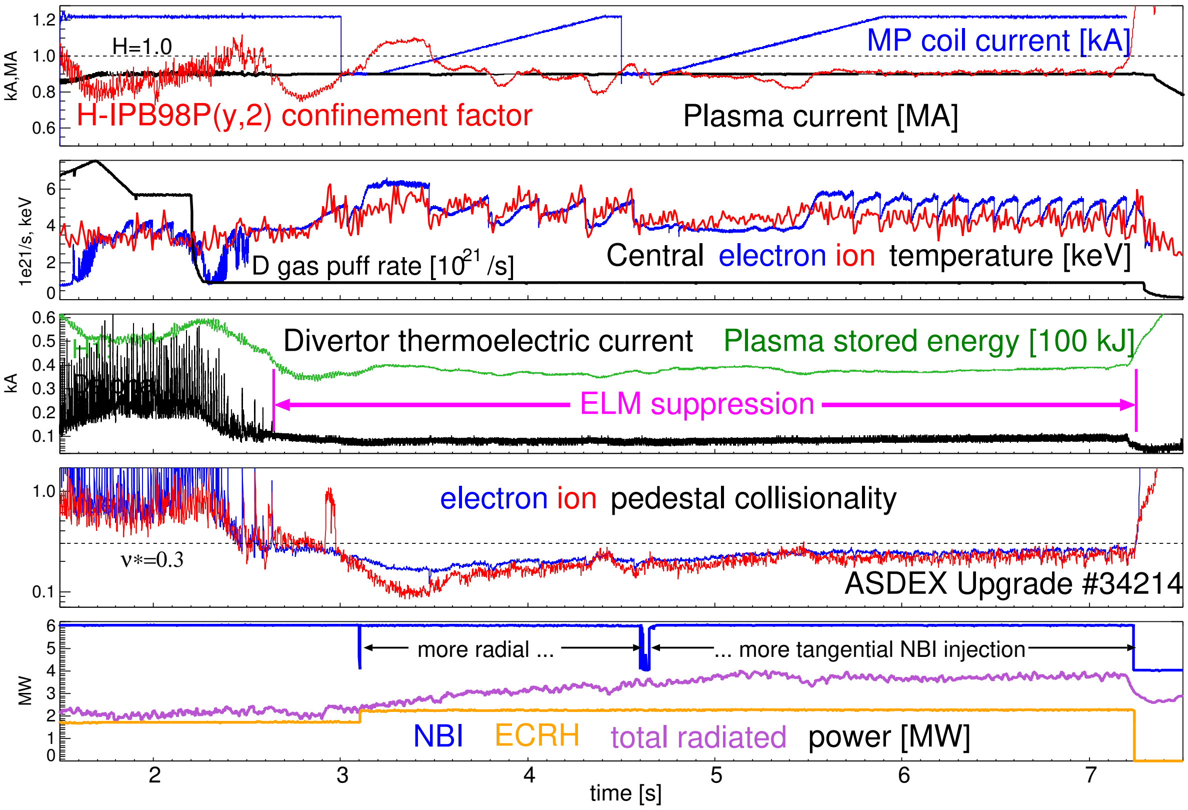

Figure 1: ELM suppression for full flat-top obtained in shot 34214.

between, one of the tangential NB sources is replaced with a radial source. At 3.1 s, the ECRH power is increased. As seen from central T_e and T_i traces, the choice of NB injection modifies slightly the sawtooth crash frequency. Sawtooth crashes cause redistribution of particles and stored energy as seen in many measurements, however in this and many other discharges no ELMs are triggered. For each of the NB configurations the MP coil current is reduced from initially $I_{MP} = 1.22$ kA to 0.9 kA and slowly ramped up. ELM suppression is maintained at all times. At low I_{MP} during the radial NB phase, the H-mode confinement factor rises transiently to $H_{98Py,2} = 1.1$, the highest value obtained with MP ELM suppression in ASDEX Upgrade so far. This rise occurs during a phase without sawtooth crash and is associated with increased pedestal T_i, which leads to reduced $\nu^*_{\mathrm{i,ped}}$.

In order to detect the existence of edge safety factor access windows for ELM suppression, first experiments with plasma current ramps have been carried out. In pulse 34205 (Fig. 2), q_{95} is ramped from 3.79 to 3.6. Once the plasma density has decreased sufficiently, ELM suppression is obtained and maintained for the entire q_{95} ramp. This result does not rule out the existence of q_{95} access windows but shows that matching a particular q_{95} value is not an overly critical requirement for achieving ELM suppression. It should be noted that I_{MP} is ramped down as I_p (and therefore, B_θ) is increased in order to remain safely below the $j \times B$ force limit of the MP saddle coils. As the plasma current increases, the plasma density increases, as well as the ion pedestal temperature and thereby the MHD stored energy.

Variation of I_{MP}, NB geometry and I_p all result in a variation of the plasma rotation. We can therefore examine if ELM suppression implies certain features of the plasma flow profiles, most notably the absence of flows that shield the MP at rational surfaces near the inner boundary of the H-mode transport barrier. The existence of an unshielded resistive MP response, i.e. a macroscopic magnetic island that blocks the expansion of the H-mode barrier

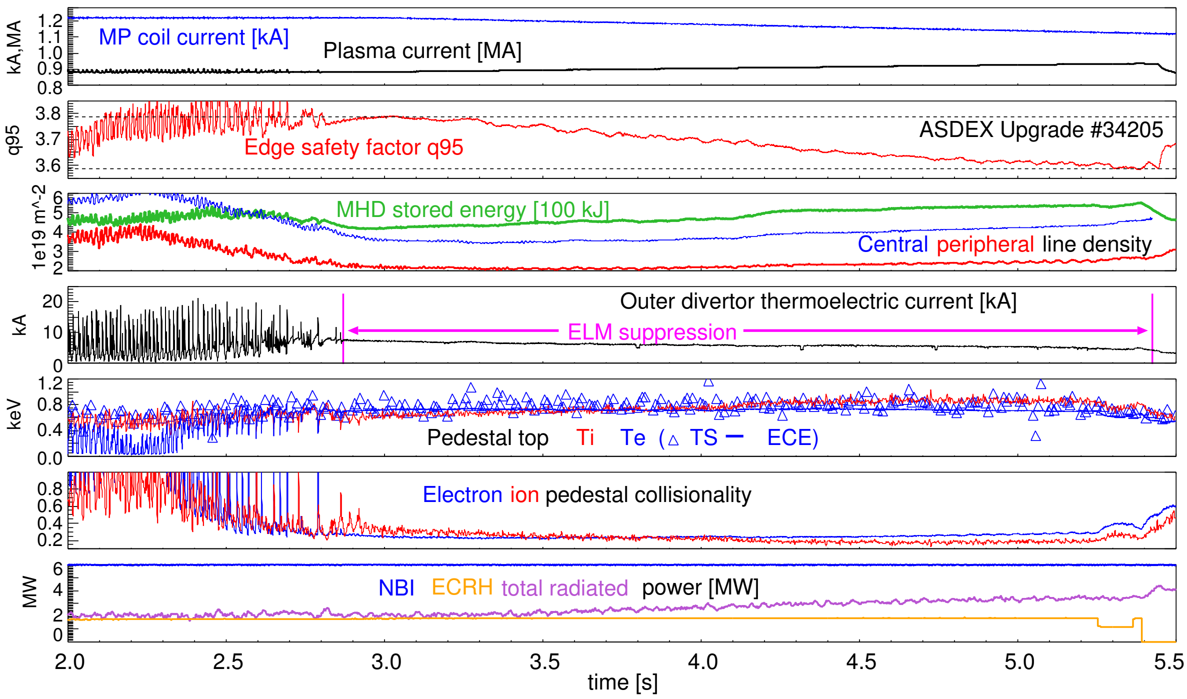

Figure 2: Edge safety factor (q_{95}) ramp in shot 34205.

towards destabilisation of ELMs has been invoked as an explanation for ELM suppression [6]. In a two-fluid MHD picture [7], the resistive resonant response is expected to be strongest for zero electron perpendicular flow $v_{e,\perp}$, while finite $v_{e,\perp}$ will result in shielding currents driven by induced $v \times B$ e.m.f. Kinetic modeling [8] suggests that a guiding centre resonance with the applied field, i.e. $\omega_{E\times B} = 0$, can drive transport and this may potentially also affect the plasma response to the MP.

In Fig. 3 four extreme cases of plasma rotation are compiled from the plasma discharges described above, beginning and end of the I_p ramp in pulse 34205, and one phase each with low and high I_{MP} of pulse 34214. All profiles are plotted vs. normalised poloidal flux ψ_n. The location of resonant surfaces is indicated by dashed vertical lines for each case. In the left panel, profiles of the toroidal rotation frequency of boron (B^{5+}) are shown, as fitted to measurements of core and edge charge exchange recombination spectroscopy (CXRS) on one of the heating beams. The inversion of the toroidal impurity flow from positive (co-I_p, projected ion diamagnetic direction) in the core to negative (ctr-I_p, projected electron diamagnetic direction) in the edge barrier region at $\Psi_n = 0.95$ is a feature of the applied MP and is often observed in ELM mitigation and ELM suppression experiments [4]. The poloidal rotation frequency is calculated with the NEOART code [9] and found to be consistent with measurements which are available at the plasma edge. The $E \times B$ rotation frequency (middle panel) is calculated from toroidal and poloidal rotation and the impurity diamagnetic flow, using the impurity ion force balance [10]. Even for boron, a light impurity, the diamagnetic flow is much smaller than the main ion or electron diamagnetic flow, and consequently, the $E \times B$ velocity in the plasma core is in co-I_p direction and only slightly smaller than the impurity flow. On the other hand, the strong edge gradient in the H-mode barrier drives ctr-I_p $E \times B$ flow and therefore causes $\omega_{E\times B}$ to change sign near the pedestal top in all cases. The radius of the $\omega_{E\times B} = 0$ position varies and it is not clearly aligned with the radius of a resonant surface. Finally, in the right panel, profiles of the electron perpendicular flow frequency are shown, calculated from $\omega_{E\times B}$ using the electron radial force balance and electron diamagnetic flow

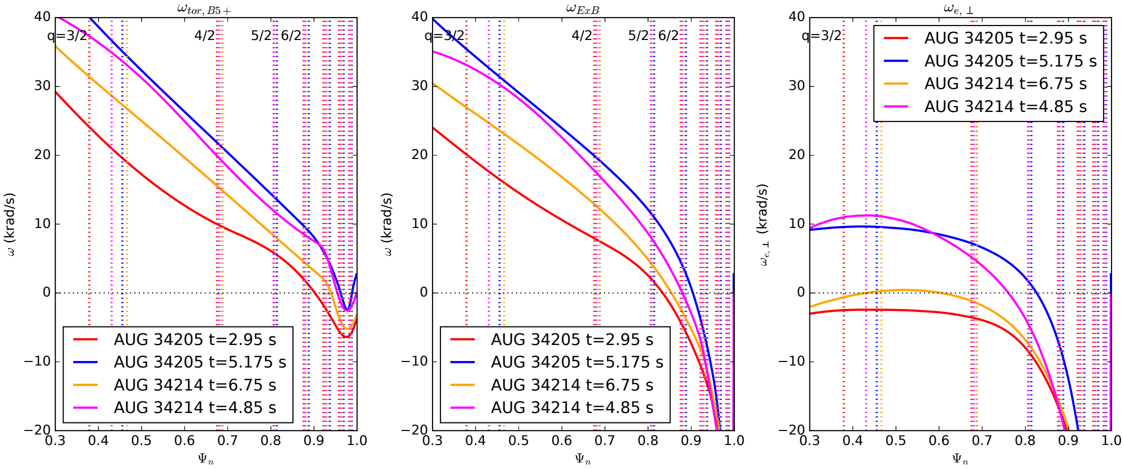

Figure 3: Rotation angular frequency profiles for various phases of shots 34205 and 34214. Left: Toroidal rotation of boron impurity (B^{5+}) as measured by CXRS. Middle: $E \times B$ rotation. Right: Perpendicular electron flow.

obtained from electron density and temperature profiles. For shot 34005, $t = 2.95$ s, $\omega_{e,\perp}$ does not cross zero. For shot 34214, $t = 6.75$ s, $\omega_{e,\perp} \approx 0$ in a wider radial range, but not close to the pedestal top. In the remaining two cases there is a zero-crossing, albeit not clearly at resonant surfaces. In all four cases, plasma temperature and density profiles maintain finite gradients throughout the core. The absence of profile flattening suggests that at least no large magnetic islands have formed.

In summary, ELM suppression is now reliably obtained in ASDEX Upgrade in H-mode plasmas at low density, corresponding to a pedestal collisionality $\nu^*_{\mathrm{ped}} = 0.3$ or below, with $n = 2$ magnetic perturbations. Whether this is a threshold in plasma density or collisionality or another related quantity is not yet known and needs to be further investigated. Similar to many observations in DIII-D [1], the plasma density and the confinement are affected by a clear “density pump-out” effect, and an increase of the pedestal ion temperature can recover the plasma stored energy. However, the experimental data base for ELM suppression in AUG is still small, and centered around a discharge type with moderately triangular cross section at $q_{95} = 3.7$. First experiments have been carried out to test sensitivity of ELM suppression access against variations of plasma rotation. So far, there are no indications for a critical role of plasma rotation, such as to produce or avoid helical shielding currents at resonant surfaces.

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