Evidence for increased fuelling by application of magnetic perturbations at high density at ASDEX Upgrade

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Magnetic perturbations (MP) are a tool for ELM mitigation, which is currently investigated in several tokamaks worldwide. At ASDEX Upgrade a reliable ELM mitigation regime has been found at high densities [1], while at low densities the search for a window, in which ELM mitigation is successful such as in DIII-D [2] is on-going [3]. At low densities the application of MPs can lead to a reduction of the density ('pump-out'), but at high densities an increase in the line averaged density can be observed. The high density ELM mitigation scenario at ASDEX Upgrade requires line averaged electron densities (n_e) at the pedestal larger than 65% of the Greenwald density limit (n_{GW}). [1]. Under these conditions the inner divertor is detached and a high density region is observed in the scrape-off layer (SOL) at the high field side at the height of the x-point expanding well above the x-point [4], which we will call HFS n_e front in the following. Spectroscopic measurements (Stark broadening) determine the electron density in this HFS n_e front, which is as high as $6\text{-}8{\cdot}10^{20}$ m^{-3} in the example discharge #26081, thus a factor of 30-40 larger than the density measured at the separatrix, which is $2{\cdot}10^{19}$ m^{-3}. At the same time, MP coils create helical magnetic field perturbations reaching out far into the unperturbed SOL [5]. The fact that 'density pump in', i.e. the slow increase of the core density under application of MP coils, is only observed, when the inner divertor is detached and the HFS n_e front exists, motivates the hypothesis that the HFS n_e front serves as reservoir feeding the core plasma with particles. (Note that at low density the n_e development depends on the resonance condition of the MPs [3].)

Figure 1 shows a 2D plot of the minimum normalized flux surface value, psi_N, each field line reaches calculated for an equilibrium with MP in the 'vacuum approach' (shielding currents in the confinement region are not taken into account). The 'fingers' reaching into the SOL are most clearly visible at the height of the x-point. Figure 1 illustrates that regions in the SOL are connected to regions at or even inside the unperturbed separatrix (blue line). Due to the disturbed magnetic topology, parallel transport along the field lines has a radial component. This change in magnetic topology is also visible as strike line splitting on the divertor plates. It is shown that the finger-like structures are observable in the power [6] as well as particle [7] flux to the LFS divertor tiles. This means that along the 'fingers' heat and particle transport is observed. As the measurements shown in [6,7] were carried out at the LFS divertor, and all gradients in n_e and T_e are negative and hence towards the target plate, such an observation is compatible with density 'pump-out', i.e. particles leaking from the previously confined region into the open field lines.

While the cause for the HFS n_e front is not yet clear, its existence may be a plausible cause for the observed density increase when MPs are applied and the helical magnetic field perturbations overlap with this region. Namely, the hypothesis is as follows: via perturbed field lines the confined plasma is connected to the HFS n_e front, which increases in n_e when MPs are applied, an indication that T_e is sufficiently high to ionise (10-15 eV). The pressure gradient is then in the direction towards the core ($10eV \times 8 \cdot 10^{20} m^{-3} > 100eV \times 2 \cdot 10^{19} m^{-3}$). This exceptionally high n_e reservoir can lead to an increase of the midplane n_e and thereby overcompensate the particle losses at the LFS.

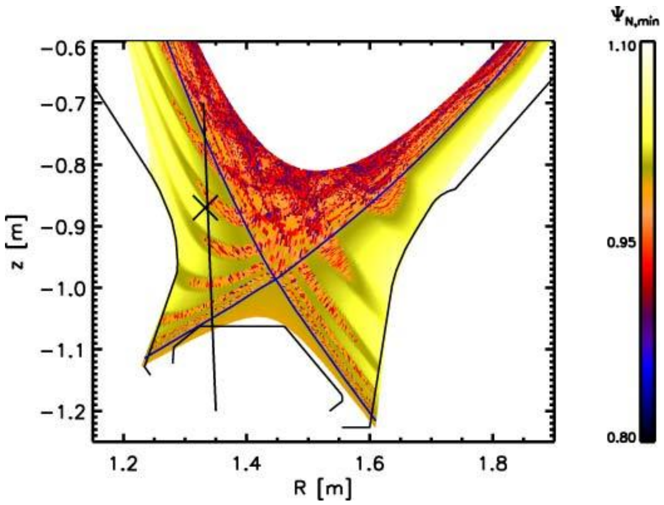

Figure 1: 2D plot of minimum psi_N to which the field lines connect. Nominal separatrix indicated by blue line. The cross marks the position of particle source in modelling (see text), the straight line on HFS is a divertor spectroscopy viewing line.

It is not straight forward to underpin the hypothesis experimentally, because the change in density is accompanied with a change in ELM signature. Figure 2 shows characteristic time traces of discharge #26081 (800kA, -2.5T, P_{aux}=9MW), in which MPs are applied from 2s on (fig 2.a). During MP application, at first the density rises only slowly (fig2.b,c), while the type-I ELM frequency drops from 60 to 40 Hz. Then type-I ELMs occur only intermittently until they are completely replaced by small events at t = 2.8 s (fig2.d), when the density again increases significantly. Figure 2.e shows the electron density from a viewing chord through the HFS n_e front region [8], its location is indicated in figure 1. The temporal development of n_e in the HFS n_e front clearly corresponds with the trace of ne_edge in the confined plasma (fig 2.b). For better visibility of the density development, fig. 2.c shows d(ne_edge)/dt derived from the smoothed signal of the interferometer edge channel. One could argue that (a) particle confinement has increased or (b) less or no type-I ELM events cause less particle losses. However, measurements with reciprocating probes have shown [7] that the ion saturation current of a probe inserted into the SOL always measures a higher particle flux when MPs are applied, regardless of whether ELMs are suppressed or not. This cannot be brought in accordance with assumption (a) of a better particle confinement nor with (b) that the mitigated ELMs cause less particle loss.

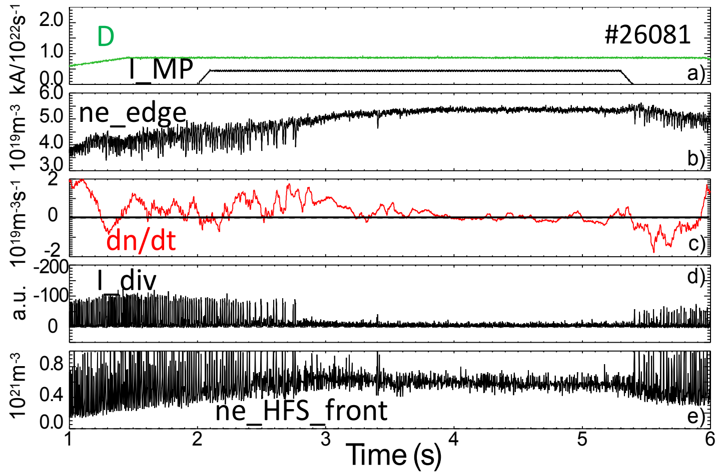

Figure 2: a) MP coil current, D gas fuelling rate, b) n_e from edge interferometer channel, c) smoothed dn/dt from b), d) divertor shunt currents as ELM indicator, e) n_e of HFS n_e front from divertor spectroscopy (Stark broadening) .

The two signals, ne_edge and ne_HFS_front are clearly correlated. With a constant gas puff (fig 2.a) and under the assumption that pumping stays the same, an increase in the SOL density can normally only be caused by particles stemming from the confined plasma region and would be accompanied by a decrease in the core plasma density. The fact that in this case the core density increases is a strong sign for an additional source, which might be the HFS n_e front connected to the core via the perturbed equilibrium.

Another explanation for the observed increase of the core density could be that more neutrals penetrate into the confined region, because of the non-uniform magnetic SOL structure. This is currently under investigation, but Lunt et al [9] find that -on the contrary- the neutral penetration flux is reduced with MPs.

Modelling of the plasma- and neutral particle transport of the AUG SOL was carried out by the 3D code EMC3-Eirene [6] comparing the situation with and without MPs. Recent simulations show a density pump-out effect of the MP under non-detached divertor conditions, i.e. decrease of the separatrix density when the MPs are switched on while keeping the total recycling flux constant [9]. Assuming a particle source of several ten percent of the total recycling flux at the position R=1.33 m and z=-0.87 m, indicated by a cross in figure 1, where the HFS n_e front is observed in the experiment, the pump-out effect decreases. Given, however, that the physical mechanism to maintain the HFS n_e front is neither understood nor implemented in the code, the assumption of such a local particle source can only be a crude and possibly inconsistent approximation. Consequently, the predicted HFS target profiles deviate strongly from the measured ones.

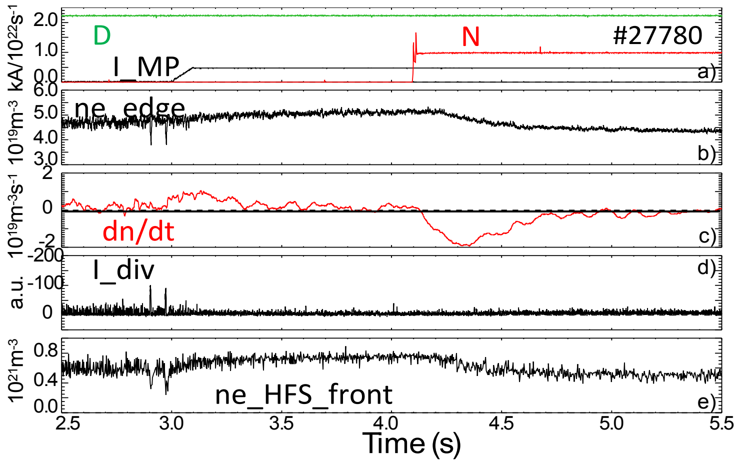

Figure 3: a) MP coil current, D and N gas fuelling rate, b) n_e from edge interferometer channel, c) smoothed dn/dt from b), d) divertor shunt currents as ELM indicator, e) n_e of HFS n_e front from divertor spectroscopy (Stark broadening).

A modification of the HFS n_e front can be achieved by nitrogen seeding. It has been shown in [4,8] that N seeding leads to a reduction of the HFS n_e front. Figure 3 shows the same time traces as figure 2 but for discharge #27780 (800 kA, -2.5T, P_{aux}=10.2 MW). In this discharge before the MPs are turned on the density is higher than in #26081 and no type-I ELMs are observed, but smaller, high frequent ELMs are already present. Also the HFS n_e front is present, visible in fig. 3.e. With the application of MPs at 3s, again both the traces of ne_edge (fig. 3.b) and ne_HFS_front (fig 3.e) increase. At t = 4.1s a nitrogen gas puff starts (fig. 3.a), causing a reduction of the density in the HFS n_e front. Concomitantly, also the core density decreases, again showing the close relation of the HFS n_e front density and the core density when MPs are applied.

In summary, this paper tries to underpin the hypothesis, that the application of MPs in plasmas, where the core density is below the threshold found for ELM mitigation but high enough to exhibit a density front in the HFS SOL, leads to an increase in core density and thus finally to plasma conditions where only small, mitigated ELMs are found.

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