# EDGE DENSITY CHARACTERIZATION CLOSE TO THE GREENWALD DENSITY LIMIT WITH THE NEW CLOSED DIVERTOR IN ASDEX UPGRADE

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## 1. Introduction

In order to achieve thermonuclear burn, future fusion experiments must safely operate at rather high density, while retaining sufficiently high energy confinement $\tau_E$. Present experiments, however, show that the useful tokamak operation space is limited towards high density by various processes, for example by exessive edge radiation cooling eventually causing a disruption, by the onset of fast MHD-istabilities (e.g. ballooning limit) or simply by intolerable energy confinement degradation (e.g. loss of H-mode). Despite the obvious role of the edge energy balance in most disruptive discharges, the empirical heating power independent Greenwald line averaged density limit scaling ($\overline{n}_e^{GW} = I_p \,/\, (\pi a^2)$ $[10^{20} m^{-3}, MA, m]$), which primarily has been developed for OH and L-mode discharges, has been shown to be quite successful in describing experimental data. Greenwald et al. suggested a severe degradation of particle confinement when approaching this limit [1].

Meanwhile, $\overline{n}_e$ beyond this limit have been reported from several limiter and divertor tokamaks with gas-puffing. In practically all this cases centrally peaked electron density profiles have been observed [e.g. 2], indicating a limitation of the edge density rather than of the line averaged density.

As often demonstrated injection of cryogenic pellets is also a successfull tool to surpass the Greenwald limit. However, experiments have shown that in the most probable envisaged operation scenario in ITER, the ELMy H-mode, the pellet particle fuelling efficiency degrades strongly with increasing heating power. This holds for the standard injection scheme from the magnetic low field side (LFS).

During the short process of pellet ablation these particles build a high pressure plasmoid which is subject to a radial force. This diamagnetic force points always outwards in major radius direction. Therefore we extended our system to inject pellets from the inner side of the torus, i.e. from the magnetic high field side (HFS). This new injection scheme leads to significantly improved instantaneous particle fuelling efficiency while the density build-up in the plasma may be still limited by transport degradation phenomena.

This paper presents global and local densities in the vicinity of the Greenwald limit. Since both the H- and L-mode density limit (DL) is commonly believed to be an edge physics effect, we focus our investigations on edge density and transport behaviour of low $Z_{eff}$ deuterium plasmas in the new closed divertor configuration DV-II. The results are compared with those obtained with the old open divertor configuration DV-I.

## 2. Discharge Parameters and Diagnostics

Our investigations concentrate on lower single null discharges (R = 1.65 m, a = 0.5 m, $\kappa \sim 1.6$) in deuterium with plasma currents $I_p$ of 0.6-1.2 MA and toroidal magnetic fields $B_t$ of 1.5-3 T, corresponding to safety factors $q_{95}$ between 3 and 7. NBI heating powers up to 15 MW have been applied. $\overline{n}_e$ ranges between $0.5 \cdot 10^{20} m^{-3}$ and $1.4 \cdot 10^{20} m^{-3}$. The solid deuterium pellets were injected from HFS with an inclination angle of $\approx 45^o$ with respect to the midplane directing to the plasma centre. Both feed-forward and density feed-back injection are performed with injection velocities of 240 m/s and repetition rates of up to 60 Hz, yielding penetration depths of up to half plasma radius.

The densities and temperatures mainly presented are measured by Li-beam and Thomson scattering and FIR interferometry diagnostics.

## 3. High Density Operation with Pure Gas-puffing

The H-mode is generally accessible when the input heating power $P_{heat}$ exceeds a certain limit depending on density and magnetic field $P_{heat}^{L\rightarrow H} = c \cdot \overline{n}_e\, B_t$ where the constant $c$ depends primarily on ion species and ion $\nabla$B drift direction [3]. Closely above the threshold the H-mode is characterized by high frequency type-III ELM's ($\partial\, \nu_{ELM} / \partial\, P_{heat} < 0$). Deeper in the H-mode the ELM activity changes to low frequency type-I ELMs ($\partial\, \nu_{ELM} / \partial\, P_{heat} > 0$) [4]. During density rises of H-mode plasmas up to the non disruptive H-mode density limit (i.e. H$\rightarrow$L mode back-transition) the discharges pass normally the following phases : at high density the ELM's revert from type-I back to type-III, the density at the separatrix $n_e^{sep}$ increases monotonically with $\overline{n}_e$ but tends to saturate in the high density type-III ELM phase and the divertor detaches [5], $\tau_E$ degrades with increasing recycling monotonically down to L-mode levels, the electron temperature closely inside the separatrix at the H-mode transport barrier approaches $\approx$ 200 eV at the DL.

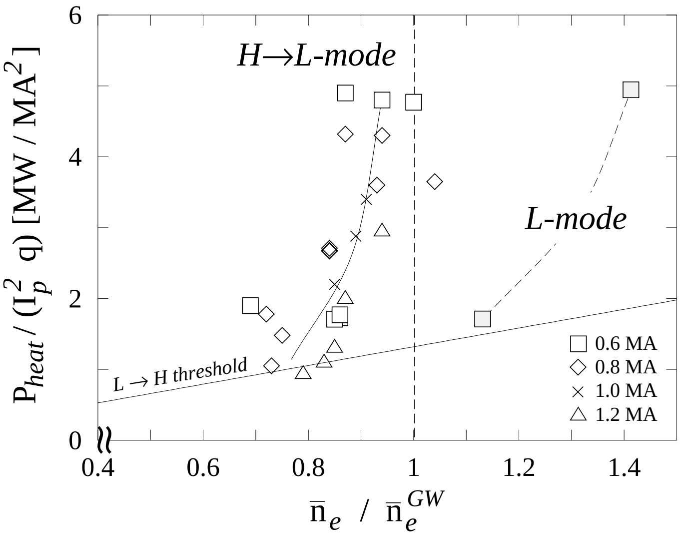


**Figure 1.** The operation diagram shows the strong deviation of the power needed to achieve H-mode from the usual $P_{heat} \propto \overline{n}_e\, B_t$ scaling close below $\overline{n}_e^{GW}$. Note that $I_p$ and $B_t$ are varied by at least a factor of 2.

Generally, slighly below the Greenwald limit the L$\leftrightarrow$H-mode threshold power deviates from the above scaling and rises dramatically (see Fig. 1), i.e. the H-mode DL becomes nearly independent of $P_{heat}$. Earlier experiments in ASDEX Upgrade have shown [6] this detrimental effect at one particular plasma current of $I_p$ = 0.8 MA. To get more insight into the responsible processes further parameter scans have been performed, especially in $I_p$, $B_t$ and $P_{heat}$. Figure 1 gives an overview over these experiments. To combine the data of different $I_p$ in one picture with a common H-mode threshold we replace in the $P_{heat} \propto \overline{n}_e\, B_t$ scaling $\overline{n}_e$ by the Greenwald expression. This leads to $P_{heat}\, /\, (I_p^2\, q_{95}) \propto \overline{n}_e\, /\, \overline{n}_e^{GW}$. Figure 1 shows nicely that the earlies findings [6] hold also for a significantly enlarged parameter space. It is interesting to note that the increase of $I_p$ by a factor of 2 yields the same normalized densities $\overline{n}_e\, /\, \overline{n}_e^{GW}$, i.e. at 1.2 MA double the line averaged density than at 0.6 MA with comparable ITER scaling normalized $\tau_E$. This is remarkable since at these high densities the edge particle fuelling profiles shift markedly outward into the scrape-off layer (SOL) and also the NBI particle ionization profiles move close to the edge. Nevertheless, with gas-puffing alone the Greenwald limit could not be exceeded.

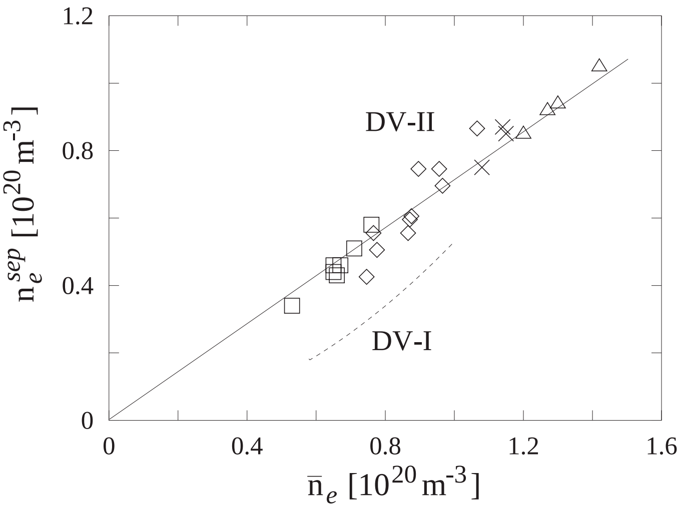


**Figure 2.** The figure shows the density profile similarity over a large density variation at the H-mode DL.

To gain further insight into the H-mode limit physics we discuss the related edge densities in more detail. The ratio of the edge density $n_e^{sep}$ to $\overline{n}_e$ is found to be practically constant, indicating a strong self similarity of the bulk density profile in a wide density range (see Fig. 2). This is in contrast to findings with the open divertor DV-I, where $n_e^{sep}$ increased quadratically with $\overline{n}_e$ and also the edge densities at a given $\overline{n}_e$ were clearly lower [6, 7]. On the other hand, $n_e^{sep}$ versus other typical SOL moments like density profile decay length $\lambda_e^{SOL}$ and the line averaged density in the SOL $\overline{n}_e^{SOL}$ show similar linear relationships as found in DV-I [8]. Typical SOL density decay lengths are 3-5 cm for the densities discussed here (see Fig. 2).

To deduce from the experimental knowledge of a constant pedestal $T_e^{DL}$ at the H-mode DL and empirical ITER confinement scalings a predictive scaling for the corresponding pedestal density $n_e^{DL}$, we rewrite the pressure under the assumption of profile similarity $< p > \propto \; T_e^{DL} \, n_e^{DL} \; \propto \; P_{heat} \, \tau_E$. This yields $n_e^{DL} \; \propto \; I_p^{\approx 1} \, P_{heat}^{0.3-0.5}$, the exponent of $P_{heat}$ depending on the actual confinement scaling used. The $I_p$ scaling agrees with the experimental findings, whereas the observed heating power dependence is with $\overline{n}_e^{DL} \; \propto \; n_e^{sep} \; \propto \; P_{heat}^{0.1}$ noticeably weaker than the above derived expression. This might reflect the fact that discharges with densities close to the Greenwald limit are only a small fraction of those used in the ITER confinement regressions.

**4. High Density Operation with HFS Pellet Injection**

Using the pellet injector in ASDEX Upgrade in density feedback mode long lasting ($>> \tau_E$) density phases beyond $\overline{n}_e^{GW}$ in H-mode are achieved (see Fig. 3). The energy confinement, however, still degrades with increasing neutral particle density [9]. Within the density build-up to e.g. $\overline{n}_e \; \approx \; 1.2 \, \overline{n}_e^{GW}$ the density profiles do, in first order, not change their shape despite the much deeper particle deposition compared to gas-puffing. The profiles remain quite flat in the core plasma with steep gradients in the edge pedestal region (see Fig. 3). These edge gradients increase, typically, strongly after the L→H transition but change only little during further $\overline{n}_e$ build-up. $\overline{n}_e$ and edge densities rise concomitantly up to $\overline{n}_e \; \approx \; 0.9 \, \overline{n}_e^{GW}$ but than $n_e^{sep}$ saturates. The constancy of the edge density (and pressure) gradient indicates a critial limit caused perhaps by e.g. ballooning induced transport. The additional $\overline{n}_e$ rise via pellets is achieved by an extension of the radial width of the steep gradient zone further inwards, see Fig 3.

The significantly different particle fuelling rates between pure gas-puffing and pellet injection on one hand and the mainly unaltered density profile form on the other hand indicates a drastic change of the particle transport behaviour during pellet injection in the vicinity and above $\overline{n}_e^{GW}$. For comparison, the total particle fuelling rate inside the steep gradient zone owing to pellet injection ($\Phi \; \approx \; 10^{22}/s$) is roughly one order of magnitude larger than the NBI fuelling

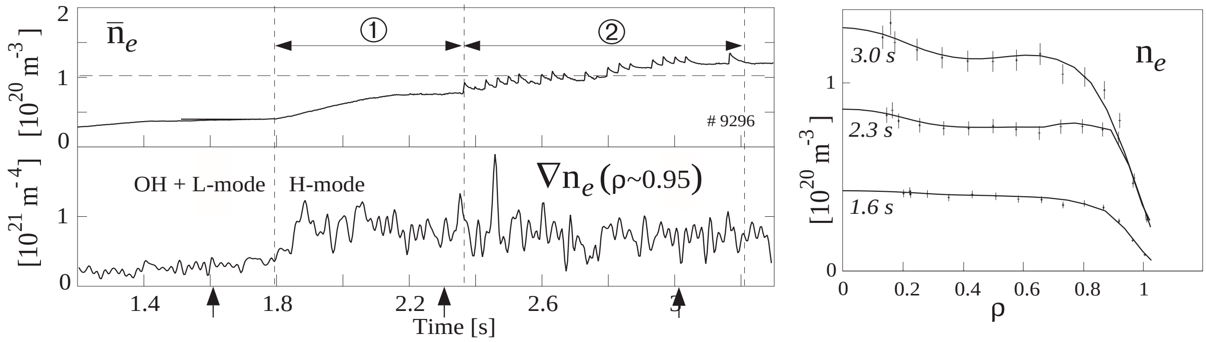


**Figure 3.** The figure shows the density development before and during the injection of a string of HFS pellets. With begin of the H-mode the edge density gradient (and pressure gradient) increases and stays constant also during the further $\overline{n}_e$ increase. The corresponding density profiles show clearly a widening of the edge gradient zone after pellet injection.

rate ($\Phi \approx 10^{21}/s$ at 10 MW) or even the recycling fluxes. Taking the slow density rise of the discharge in Fig. 3 as example and neglecting an inward pinch velocity, the particle flux across the edge can be approximated by $\Gamma_e = D\,\nabla n_e$, $D$ being the effective particle diffusion coefficient in the edge. Since the edge gradient does not change noticeably between the purely gas fuelled (phase 1 in Fig. 3) and the pellet fuelled phase (2), but the particle source strength, i.e. the necessary particle flux through the boundary, does, it follows that the diffusion coefficient increases here by roughly a factor of $\approx 5$ to explain the particle balance. In contrast, determination of the edge diffusion coefficient during pellet injection clearly below the Greenwald limit exhibits values consistent with corresponding purely gas fuelled cases. Analyses for high densities are in progress.

## 5. Summary

Systematic global and local analyses of H-mode density limit plasmas (H→L-mode back-transition) with pure gas refuelling and with pellet injection from the magnetic high field side are performed in the new closed divertor configuration. With gas-puffing alone, $\overline{n}_e^{GW}$ could not be surpassed. In the new divertor higher edge and SOL densities are normally found compared with the old open divertor. With gas-puffing the L↔H-mode power scaling $P_{heat} \propto \overline{n}_e\,B_t$ is not longer valid if one approaches the Greenwald limit. The threshold power deviates dramatically from the prediction to higher powers which makes it difficult to maintain the H-mode at high densities. The steep edge density gradient which establishes after the L→H-transition does not increase further with concomitant $\overline{n}_e$ increase indicating the reach of a critial limit. With pellet injection $\overline{n}_e^{GW}$ can be exceeded. These discharges show $n_e$-profiles with the same edge gradient but a radially enlarged gradient zone. The strongly enhanced particle fuelling rate during pellet injection compared with the gas-puff case induces in the vicinity of $\overline{n}_e^{GW}$ a significantly increased edge particle diffusivity. Pellet injection, however, does not prevent the degradation of $\tau_E$ at high $\overline{n}_e$. Further optimizations can probably combine pellet injection with conserved high $\tau_E$.

## References

[1] M. Greenwald et al.: Nuclear Fusion **28** (1988) 2199
[2] P.C. de Vries et al.: Phys. Rev. Lett. **80**(16) (1998) 3519
[3] F. Ryter et al.: Physica Scripta, **51** (1995) 643
[4] H. Zohm: Plasma Phys. Control. Fusion **38** 105 (1996)
[5] A. Herrmann et al.: *this conference*
[6] V. Mertens et al.: Nucl. Fus. **37** 1607 (1997)
[7] J. Schweinzer et al.: PSI (1998), San Diego, USA
[8] V. Mertens et al.: *Proc. 24rd Europ. Conf. Controlled Fusion and Plasma Physics,* Berchtesgaden 1997) **21A** IV 1389
[9] P.T. Lang et al.: *this conference*