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Accessibility of high density H-mode operation by HFS pellet refueling

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1. Introduction

Operating a tokamak safely in the vicinity of the gas puff density limit in the high confinement (H)-mode offers significant advantages for a future fusion reactor. A study of the H-mode gas-puff density limit at ASDEX Upgrade showed the plasma edge [1] to dominate the confinement. Increasing the density in the H-mode was accompanied by an increasing edge density, correlated with a decrease of energy confinement [2]. The observed deadlock between edge density and line averaged density $\bar{n}_e$ can be broken off by injection of pellets produced from frozen hydrogen isotopes allowing for particle deposition deep inside the core plasma. Injection from the torus outside was found ineffective in hot plasmas due to a fast radial outward drift [3] while pellet injection from the magnetic high field side (HFS) showed a greatly enhanced performance [4].

2. Experimental set up and technical equipment

Experiments were performed on ASDEX Upgrade (R_0 = 1.65 m, a_0 = 0.5 m, κ = 1.6, V_{Plasma} = 13 m^3) in lower single-null configuration with the closely baffled divertor II ("Lyra"). A cryopump with 100 m^3/s pumping speed was optionally available for particle exhaust, in addition to 14 external turbomolecular pumps with together 12 m^3/s. The centrifuge pellet injector was recently modified to enable high particle fluxes in the inboard lauch scenario, now capable to yield a pellet particle flux $\Phi \approx 10^{22}$/s into the plasma for about 2 s. Feedback density control was performed by pellet injection initiated by the fast (cycle time 2 ms) ASDEX Upgrade control system [5]. The feedback loop response time was dominated by the pellet injector, the delay between pellet request and arrival at the separatrix was about 80 ms. Gas puff fueling and impurity puffing were performed preprogrammed or feedback controlled via several calibrated valves.

3. Experimental results

A systematic study was performed to find a scenario for density control at a level well above the Greenwald limit whilst avoiding degradation of particle and energy confinement. The influence of different target plasma conditions on the refueling behaviour was studied by changing the boundary conditions such as the neutral gas pressure, the level of radiative energy losses and/or the requested density.

The first step was to achieve stable steady state operation close to or beyond $\bar{n}_e^{Gw}$; our investigations concentrated on discharges in deuterium with $I_P = 0.8$ MA, $B_t \approx -2.0$ T, $q_{95} \approx 4$, NBI heating (D_0 injection) at a level of 5, 7.5 and 10 MW and injection of deuterium pellets. The availabe pellet particle flux was sufficient for a persistent density build-up for all target plasma conditions. The plasma peak density was found to decay after each pellet towards the base value $\bar{n}_e^b$ determined in equivalent discharges without

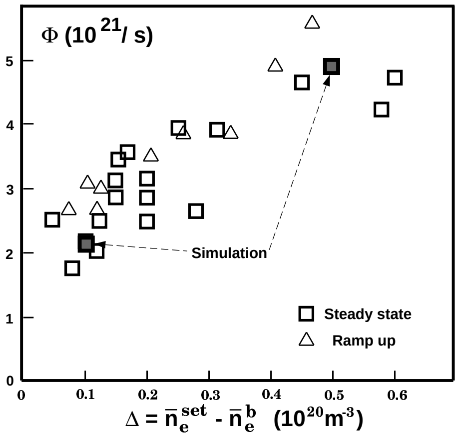

Figure 1: *Pellet particle flux Φ versus pellet induced density surplus Δ. Data taken from steady state discharges (open squares) and from discharges with slow density ramp up (triangles).*

pellet injection. This decay can be fitted for a pellet at t_0 by the expression:

$$\bar{n}_e(t) = \bar{n}_e^b(t_0) + Ae^{-(t-t_0)/10ms} + (\Delta - A)e^{-(t-t_0)/120ms} \quad (1)$$

the amplitude A is typically 10^{19} m^{-3}. The enhancement Δ of the requested density $\bar{n}_e^{set}$ correlated with the required pellet particle flux Φ is shown in fig. 1. The data set of the $\Phi - \Delta$-diagram contains controlled steady state discharges of about 2 s duration as well as shots with a slow density ramp up. Irrespectively, the discharges contained various target plasma conditions as well as different refueling scenarios with respect to $\bar{n}_e^{set}$. Modelling of $\bar{n}_e$ was performed using (1) to calculate the density evolution, $\bar{n}_e^{set}$ and $\bar{n}_e^b$ as input parameters, and taking into account the system response time. The model reproduces the required particle flux (see fig. 1) and also the density evolution quite well.

Pellet refueling showed a remarkably improved plasma energy confinement compared to gas puffing. Stable quasi-steady state H-mode operation beyond the Greenwald density was achieved. However, reduction of energy confinement was caused occasionally by at least one of the four following reasons:

1. Degradation of W_{MHD} of the target plasma by unfavourable performance of the discharge, e.g. too strong gas or impurity puffing.
2. Increase of neutral gas pressure and hence edge density at insufficient pumping caused by a parasitic pellet born gas puff.
3. Triggering of neoclassical tearing modes by the pellets.
4. Bursts of several strong ELMs expelling particles and energy following pellet injection.

Whereas the first three problems can be avoided by an accordingly tailored discharge evolution, the last one occured in each discharge, causing the at present minumum achievable performance limitation using pellet refueling. The typical signature and effect of the pellet induced ELMs is shown on the example of #10533 in fig. 2. After pellet injection, $\bar{n}_e$ stayed almost constant for about 4 ms. Then, a rapid density decrease occured, expelling typically 6×10^{19} particles within 2-3 ms. This short phase with strong particle flux (typically 3×10^{22}/s) from the plasma was followed again by a quiet phase until the next rapid density decay. The strong particle flux was correlated to the presence of strong ELM activity as seen from the Mirnov coil signal. Interestingly, on the injection of a pellet three or more ELM's were recorded, the first directly with the pellet (at the resolution available), the next ones could be correlated each to the start of one rapid density decay phase as described above, until the next pellet was registered. It must be noted, that the post-pellet ELM's lasted much longer than the pellet triggered ELM which did not differ

significantly from an usual "background ELM" typical for the present plasma conditions. Also, only the post-pellet ELM's were responsible for the rapid density drop.
An example of the ELM burst induced confinement degradation is the first density ramp up cycle in the discharge #10636. Figure 3 shows time traces of $\bar{n}_e, W_{MHD}$ as well as the applied NI heating power and the signal from the D_α pellet monitor. The first pellet sequence drove $\bar{n}_e$ far beyond the Greenwald density while the typical H-mode signature was maintained. With the start of the pellet sequence, a decay of the plasma energy set in to a level approx. 10% below the initial value. Once this level was reached, no further degradation took place despite further pellets arriving in the plasma. After the pellet sequence, density decay towards $\bar{n}_e^b$ set in. About 20 ms after the last pellet, the contribution of the fast component almost vanished and the slower decay took over, whilst the energy remained at the reduced level. 130 ms after the last pellet, the density was still slightly above $\bar{n}_e^{Gw}$. At that time the plasma energy had completely recovered due to a faster time scale.

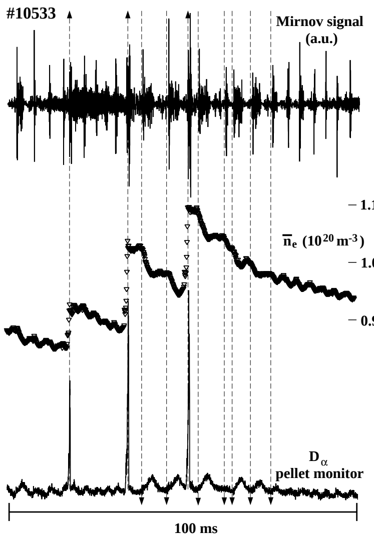

Figure 2: *Correlation between enhanced ELM activity and rapid plasma density decay after injection of pellets on the example of #10533. Mirnov coil signal shows the intensity of MHD activity, density is monitored by DCN-interferometer and pellets by D_α-monitor.*

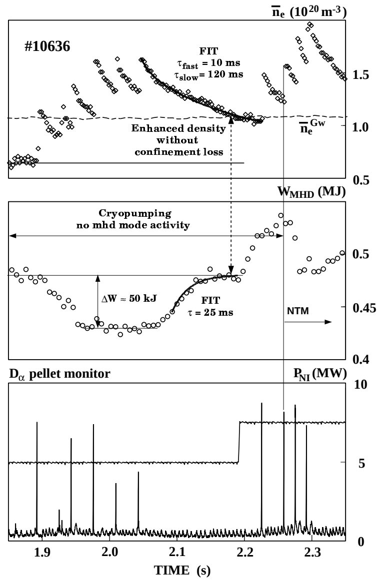

Figure 3: *Temporal evolution of plasma density, plasma energy, applied NI heating power and the signal from the D_α pellet monitor during the first density ramp up cycle of #10636.*

Considering the first pellet sequence of discharge #10636, the pellet induced loss power can be estimated as 0.5 MW while an averaged particle outflux from the plasma of 2×10^{21}/s was observed. These particles, first thermalized and then partially lost during the ELM, could yield a convective loss power of $3\Phi_{loss}k_BT \approx 0.77$ MW. Thus, ELM bursts are likely to cause both, the observed particle and the energy losses. This interpretation would match very well with the observed slowing down of the density decay and the recovery of plasma energy once the bursts come to an end.
The pellet fueling cycle under optimum conditions achieved so far in the first pellet sequence of #10636 is shown in a plasma energy vs. $\bar{n}_e$ operational diagram in fig. 4. Starting from initial conditions like in a respective gas puffed discharge ⟨1⟩, the six in-

jected pellets (P1-P6) ramp the density up far beyond $\bar{n}_e^{Gw}$ with a confinement degradation much less than by gas refueling ⟨2⟩. At the end of the pellet train transiently enhanced density without confinement loss can be achieved ⟨3⟩. Without further pellet injection the discharge returns to its previous state while recurrent injection of pellets would keep the discharge on this fueling cycle.

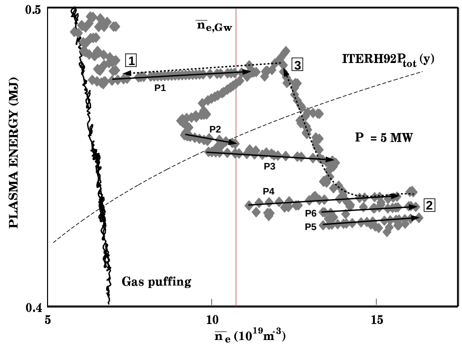

Figure 4: *First density ramp up cycle of #10636 in a W_{MHD} vs. $\bar{n}_e$ operational diagram. Clear improvement with respect to gas puffing is evident, transiently enhanced density without confinement loss is achieved. Also shown are calculated plasma energies applying the ELMy ITERH92 power scaling.*

Further enhancement of this cycle should be achieved by moldering the ELM effect on the confinement, e.g. by deeper pellet injection. This requires presumabely higher pellet velocities than available at present. An according setup improvement is already under construction.

4. Summary

Pellet injection from the magnetic high field side has demonstrated the potential for density control beyond the Greenwald density without loosing H-mode features. Density relaxation after each pellet injection took place first on a fast (τ = 10 ms), then on a slower (τ = 120 ms) time scale. The global density evolution can be understood taking into account the density relaxation, the injection system response time and effective particle flux. Analysis of the density profiles after pellet particle deposition showed the edge gradient staying essentially stiff throughout; attempts to model the according particle transport by a diffusive ansatz turned out to be inadequate. Energy confinement was considerabely improved in pellet refueled discharges achieving quasi-steady state operation at high densities with far less confinement reduction than in gas puffed discharges. On the other hand, confinement can be reduced by inappropriate experimental conditions such as NTM modes and insufficient pumping. The foremost loss mechanism was identified to be a rapid pellet particle loss caused by a burst of strong, long lasting ELMs occuring 4 ms after the pellet injection. Simultaneously, a power loss of typically 10% of the total heating power was observed, reducing the confinement accordingly. The energy sink is attributed mainly to convective transport by the lost particles. As energy recovery takes place on a shorter time scale than the density decay, transient phases of full (initial) confinement, but at still high densities are achieved.

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