Pellet Injection with Improved Confinement in ASDEX

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Introduction :

An intensive campaign to study the consequences of repetitive pellet injection was carried out on ASDEX. It was possible to improve by pellet injection considerably the plasma confinement compared to earlier investigations /1/. In addition we could advance considerably the understanding of the relevant mechanisms. The dominant difference between the earlier and the recent experiments was different recycling in the plasma boundary and the divertor. While the earlier campaign aimed at low-recycling pellet injection (LRP) to study the genuine pellet fuelling, the second campaign aimed at an improvement of the density limit.

Experimental parameter :

The investigation concentrated on ohmically heated doulble null discharges in deuterium but discharges with additional neutral beam heating are considered as well. The ASDEX device was run typically at $B_t = 2.2$ tesla, $I_p = 380$ kA, $q_a = 2.7$. The density range was extended from $\overline{n_e} = 0.1 \times 10^{20}$ m^{-3} to $\overline{n_e} = 1.2 \times 10^{20}$ m^{-3}. The pellets with about 4.5×10^{19} deuterium atoms each were accelerated by a centrifuge to a velocity of 620 $\frac{\text{m}}{\text{s}}$ /2/ and yield penetration depths of roughly half the plasma radius. Normally up to 20 pellets were injected with a repetition rate of 30 ms. In typical cases of good confinement ASDEX was carbonized.

In a first campaign discharges were performed to demonstrate the potential of very low recycling at the plasma boundary by combining divertor operation and pellet fuelling. The pellet injection started at low density. Only a poor density build-up could be attained under these conditions. Figure 1 shows the successful density build-up in a typical high-recycling pellet injection (HRP) discharge beyond the gas puff (GP) density limit. The flat electron density profile starts to peak strongly with pellet injection whereas the temperature drops somewhat but the profile stays nearly self-similar.

The increase of the energy content and the improvement of the averaged energy confinement time is clearly seen in fig. 1; $\tau_E = 1.9 \times W_e/(P_{OH} - 1.9\dot{W}_e)$. W_e : energy content of the electrons; P_{OH} : ohmic heating power without correction for radiation.

In the pure GP phase the radiation profile is strongly peaked at the edge. During and after pellet injection when sawtooth activity is reduced the central radiation increases exponentially to a value comparable to the local power input without indication of saturation. Spectroscopic observation indicates Fe and/or Ti to be responsible for the rise of central radiation. Often nearly stationary density phases up to 230 ms duration could be observed after the last pellet. This phase is characterized by a very peaked pressure profile coinciding with a relatively flat temperature profile. The final breakdown seems therefore correlated to a violation of the ballooning criterion in the plasma centre. HRP discharges with neutral beam injection below ~ 1 MW behave like ohmically heated discharges. The unsuccessful density build-up at higher neutral injection power seems to be correlated with a more peaked electron temperature profile and a specific MHD-activity triggered by the pellet.

Improved energy confinement with pellet injection was always correlated to a successful density build-up. The improvement of τ_E in HRP discharges compared to standard ohmically heated GP discharges by about a factor of 2 is demonstrated in fig. 2. The increase of τ_E starts with the first pellet and the enhancement lasts for times long compared with τ_E . The data may suggest that the pellets remove the reason for the τ_E roll-over because the peaked density profile in HRP discharges seems to establish a new type of discharge. This improvement of τ_E might be explained either by a local heat transport model or the profile consistency model of Furth /3/.

Discharges with proper edge conditioning (HRP) show distinct changes in bulk plasma particle transport with pellet injection. The observed peaking of the density profile can not be attributed to central deposition of pellets because the penetration depth is approximately half the minor radius and the peaking lasts up to 230 ms after the last pellet. Assuming that the particle transport i.e. the electron flux Γ may be interpreted by a diffusive and convective driving term with a diffusion coefficient D and an inward velocity V,

$$\Gamma(r) = -D(r) \times n'(r) - V(r) \times n(r),$$

nearly stationary phases are analyzed neglecting particle sources. Figure 3 shows typical electron density profiles and deduced ratios $\frac{V}{D}$ before and after pellet injection. In the inner two-thirds of the minor radius $\frac{V}{D}$ has increased by a factor of about 3 or more demonstrating the change in particle transport. During density build-up the following transport coefficients fit the observed electron flux in the inner region :

$$D(r) = 0.1 \text{ m}^2/\text{s} \quad \text{and} \quad V(r) = 1 \times \frac{r}{a} \text{ m/s}$$

(a: minor radius)

Reduced sawtooth activity and the correlated decreased outward flow of particles during a sawtooth disruption - compared to GP discharges - seems also to be a condition for the profile peaking. GP discharges without sawteeth show a similar peaking /4/. A macroscopic vertical electric field of the order of 10 V/m might explain an enlarged inward velocity. Calculation of the neoclassical current profiles show a small but significant increase of q on axis which reflects the increase of the collisionality with pellet injection.

In typical GP discharges there is a strict relation between the bulk plasma density and the edge density $n_s = 0.3 \times \overline{n_e}$. n_s is the density at the separatrix and $\overline{n_e}$ is the line-averaged bulk density /5/. The relative exponential density decay length in the scrape-off layer is practically independent of $\overline{n_e}$. In LRP discharges the particle density in the boundary exhibits large variation during pellet injection because the divertor walls are far from saturation and the neutral flux density in the divertor is low. This lack of saturation leads to a continuous outflow of the injected particles as seen in fig. 4a . In HRP discharges the high neutral flux density prevent loss of particles. The edge density stays nearly constant during the build-up of bulk density (fig. 4b) and the very small modulation of the edge density during pellet cycle indicate that the particle density in the boundary seems to be in equilibrium with the bulk density and the recycling. While the edge density behaviour is similar to GP discharges the ratio $n_s/\overline{n_e}$ decreases from its standard GP value consistent with the peaking of the bulk profile.

References :

/1/ G. Vlases et al, Proc. 12th Europ. Conf. on Contr. Fusion and Plasma Physics, Budapest 1985, 1 (1985) 78

/2/ W. Amenda, R.S. Lang, Proc. 13th Symp. on Fusion Technology, Varese 1984, 243

/3/ M. Kaufmann et al, Nucl. Fusion, to be published

/4/ F. Wagner et al, Proc. Invited Papers, 13th European Conf. on Contr. Fusion and Plasma Heating, Schliersee 1986, vol 28 9A, 1225

/5/ K. McCormick et al, J. Nucl. Mater., 145-147 (1987), 215

Figure Captions :

1 : The electron particle content N_e and the energy content W_e are shown together with the global energy confinement time τ_E as function of time. The density and temperature profile development can be seen from the $\frac{n_e(0)}{\overline{n_e}}$ and the $\frac{T_e(0)}{T_e(a/2)}$ traces.

2 : Energy confinement time τ_E as function of the line averaged density $\overline{n_e}$ for LRP, HRP and standard ASDEX GP discharges. All discharges are with ohmic heating only.

3 : The ratio of the inward drift velocity to the particle diffusion coefficient $\frac{V}{D} = \frac{n_e'}{n_e}$ together with density profiles (*dotted lines*) is given before (a) and after pellet injection (b).

4 : Electron density profiles at the plasma boundary for LRP (a) and HRP (b) discharges. In case (a) one pellet cycle is shown. The profile steepens by the pellet and flattens afterwords again. R_S : radius of the separatrix, t_p : pellet injection time.

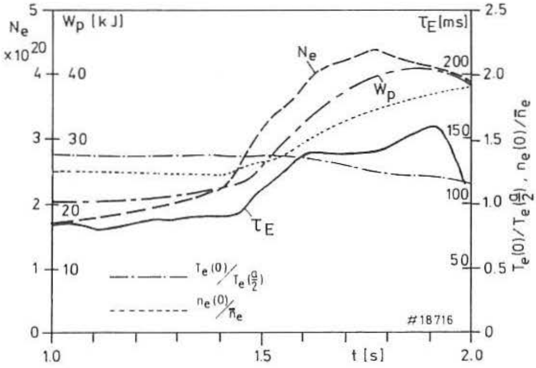

Fig. 1

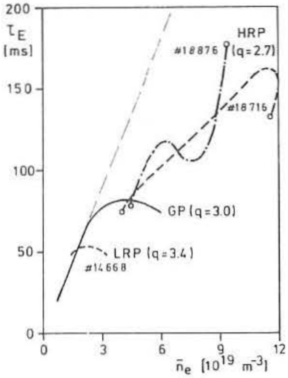

Fig. 2

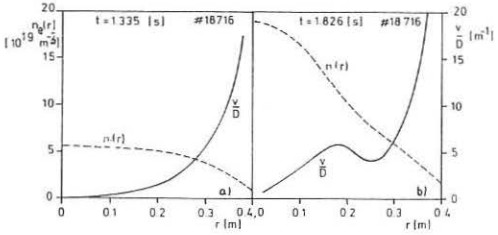

Fig. 3

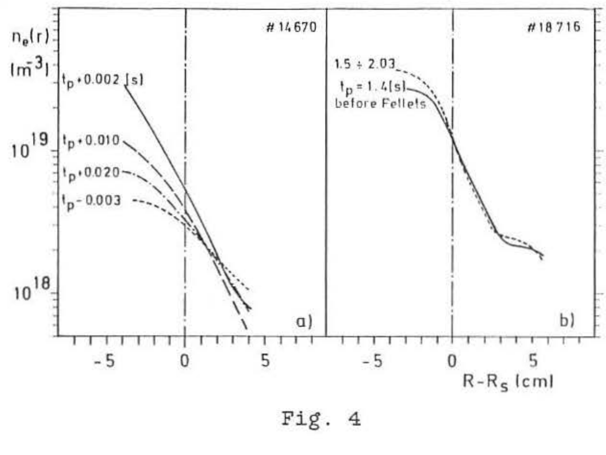

Fig. 4