INCREASE OF THE DENSITY LIMIT IN ASDEX BY REPETITIVE PELLET INJECTION

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Introduction: Investigations performed on ASDEX in a large range of plasma parameters with and without neutral beam heating showed that the density limit is normally caused by energy losses at the plasma boundary /1/. The stronger gas influx needed to achieve higher densities leads to increasing recycling losses and increasing radiation at the edge. At a certain average density the discharge becomes unstable. It seems to be obvious that more efficient refuelling deeper inside the discharge, e.g. by injection of fast pellets, should result in a higher density limit. High densities have been achieved in several experiments by a fast density ramp up with a few pellets /2/,/3/,/4/,/5/. In ASDEX also slow ramp up with a large number of pellets was applied and pellet injection was switched off or continued with reduced frequency before the density limit was reached. Very high densities, favourable peaked density profiles and improved energy confinement were obtained even after stopping pellet injection. We conclude that pellet injection can change the transport properties of the plasma fundamentally.

The experiment: In ohmically or beam heated divertor discharges the deuterium density was first ramped up by gas puffing to a value safely below the limit. Then deuterium pellets were injected to further increase the density as slowly as possible until a disruption was detected. Gas puffing during the pellet injection phase has been optimized in contrast to earlier work /6/ where it has been attempted to minimise recycling. The pellets (diameter 1.0 mm, length 1.0 mm) are cut from an extruded rod of frozen deuterium and accelerated by a centrifuge to a velocity of typically 650 m/s /7,8/. They can be individually triggered with a minimum time interval of 20 ms. The mass of each is measured with a microwave interferometer system developped by the RISØ National Laboratory. One rod is sufficient for 80 pellets which may be injected in one burst. Normally 20 to 30 pellets were injected with a repetition rate of one per 30 ms. In some discharges the repetition rate was reduced after a few pellets or injection was switched off to keep the plasma density constant. The $5\cdot10^{19}$ particles of one typical pellet correspond to a volume averaged density of $1\cdot10^{13}$ cm^{-3}.

Line averaged densities: Figure 1 shows a Hugill plot of divertor discharges at the density limit. All ohmically heated discharges in non-carbonised

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vessel with gas refuelling lie close to the solid line. The points marked with figures indicate the best discharges achieved so far with pellet refuelling in three different scenarios: ohmically and beam heated plasmas in non-carbonised vessel and ohmically heated plasma in carbonised vessel. For optimization the pellet frequency and the amount of additional gas puffing have been varied. The benefit of wall carbonisation for ohmically heated pellet discharges is clear and much higher than for gas puffed discharges (not shown in Fig. 1). Low power beam heating increased nR/B_T to about 9 in pellet refuelled discharges without wall carbonisation. It was not yet possible to exceed this value with wall carbonisation. High power co-injection did not permit to reach high densities without heavy gas puffing, so that no substantial improvement could be achieved with pellet injection at high beam powers.

Profiles: Pellet injection permits a much larger relative increase of the fusion relevant central density than of the line averaged density usually plotted in Hugill diagrams. A comparison of density and electron temperature profiles from two shots close to the density limit, one with gas puffing alone, the other one with pellet refuelling, reveals dramatic differences (Fig. 2). Density profiles with efficient pellet refuelling are strongly peaked in contrast to the rather flat gas puffing profiles. T_e profiles of gas puffing shots normally stay peaked up to the disruptive end while T_e profiles of pellet shots flatten shortly before the disruption. The time evolution of a pellet refuelled discharge which was driven close to but not into the density limit is shown in Figs. 3 and 4. Before pellet injection (A) we observe a flat n_e and a peaked T_e profile. The radiation profile (P_{rad}) is peaked at the edge with negligible radiation on axis. During pellet injection (B) the density profile peaks, the central radiation increases exponentially, the T_e profile stays peaked as long as the radiation profile is hollow. These characteristic features are observed during the pellet injection phase and even a few hundred milliseconds after its end. Finally (C) the central radiation has strongly increased to a value comparable to the local power input and flattened the temperature profile. T_e- and n_e-profiles are similar to the ones at the density limit shown in Fig. 2. Now the discharge disrupts at a density below the limit reached with continuous density increase. The radiation source has been spectroscopically identified as iron. An increase of low-Z impurities is not being observed, Z_{eff} stays close to 1.

The disruption: In contrast to gas refuelled shots a further increase of the density with pellets is not prevented by edge effects but by central radiation. With flattening T_e-profile the current density profile flattens until a stability limit is violated. A stability calculation based on fitted n_e- and T_e-profiles states that the ballooning limit is being reached. Wall carbonisation reduces the level of iron in the discharge by an order of magnitude, so that the critical level of central radiation is reached later at a higher density. It has been found that additional gas puffing also permits to reach a higher density at a certain level of radiation. We have identified high-Z impurity radiation as the limiting factor. The level of radiation observed cannot be explained by the higher density, but an increase of impurities has to be assumed. Enhanced impurity release can be excluded from spectroscopic measurements. The only possible explanation is accumulation of impurities.

Particle transport: The initial idea was to obtain peaked density profiles by moving the particle source from the boundary to the centre, but the measured profiles cannot be explained by a peaked source term. The pellets penetrate to slightly inside half the minor radius only. In the discharge phase after pellet injection the only particle source is at the edge. Assuming that the particle transport may be described by a diffusion term with a diffusion coefficient D(r) and an inward drift term with a drift velocity v(r), we analysed nearly stationary phases of a pellet shot (C in Fig. 4) and of a gas refuelled high density discharge (Fig. 2). One finds that the gas puffing profile is very well approximated with $v/D \sim r^3$, the pellet profile with $v/D \sim r$, however. Pellets, though not penetrating to the centre, apparently change the transport coefficients throughout the plasma. The effect begins with pellet injection and lasts until a few hundred milliseconds after its end, the magnitude of the effect varies, however, during the density ramp up: the density gain associated with each pellet scatters and is not proportional to the pellet size (the first ones are normally very efficient). High power co-injection seems to prevent switching of the transport properties. The impurity accumulation observed may be explained by an inward drift as well, if the ratio of drift velocity to diffusion constant is much higher for high-Z impurities than for deuterium. Because saturation has never been reached in the experiments a quantitative description is not possible.

Energy confinement: The modified transport properties do not only result in good particle confinement but also in strongly improved energy confinement. Improvement of the energy confinement is not caused by higher densities but is switched on by pellet injection as we see in Fig. 3. Absolute values of up to 160 ms were achieved in other discharges. An improvement of the global energy confinement time of 80 % was observed in ohmic discharges only. High power co-injection prevents an improvement of the energy confinement as it prevents peaking of the density profiles.

Conclusions: Pellet injection is able to switch the confinement properties of a tokamak discharge fundamentally. This switching is possible with pellets penetrating to the half-radius (there are indications that even much smaller penetration depths are sufficient). Improved particle confinement and triangular density profiles permit to achieve extremely high central densities. Substantially improved energy confinement is provided in this transport regime. The problem of impurity accumulation has to be solved which prevented to sustain this transport mode stationarily and a way has to be found to sustain the regime with high heating power.

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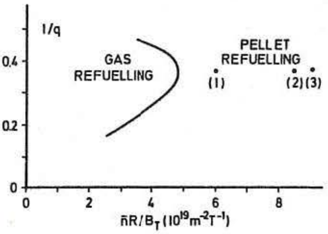

Fig. 1: Hugill plot of discharges at the density limit with gas refuelling (ohmic heating, solid line) and pellet refuelling
(1) OH non-carbonised wall
(2) OH carbonised wall
(3) NI 0.43 MW non-carbonised

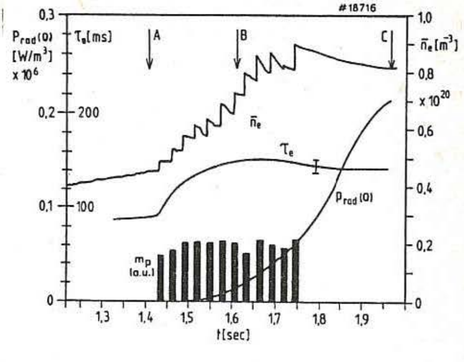

Fig. 3: Time evolution of the line averaged density n_e, radiation density on axis P_{rad}, global confinement time τ_E and pellet mass during a discharge with injection of 12 pellets.

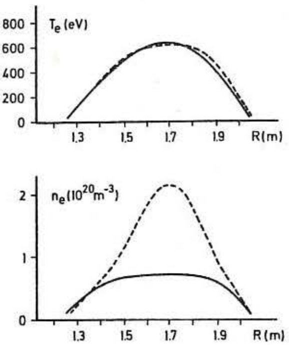

Fig. 2: T_e- and n_e-profiles of high density discharges with gas puffing (solid lines) and pellet injection (dashed lines).

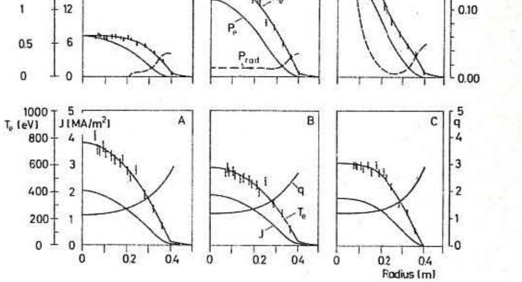

Fig. 4: Profiles of the electron density n_e, electron pressure p_e, radiation density P_{rad}, current density J, safety factor q at three times as indicated in Fig. 3.