Pellet refueling from the magnetic high field side

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Introduction

Next generation fusion devices like ITER will have to operate at densities well beyond the Greenwald density limit enfaced with gas refueling [1]. It was shown that this empirical limit can be easily overcome by injection of frozen pellets, however in discharges with high heating power and especially in type-I ELMy H-mode plasmas a large fraction of the deposited material is rapidly expelled from the plasma [2], resulting in significantly reduced fueling efficiencies ε_f. In all these experiments, pellets were injected from the magnetic low-field side (LFS), i.e. from the torus outside, which is easily accessible in a tokamak. It was argued [3] that, because of the unfavourable toroidal curvature, part of the diamagnetic pellet plasma cloud could have been expelled before it was captured by the background plasma. In this case, injection from the magnetic high-field side (HFS), i.e. the torus inside, should be much superior, since the same effect would help to transport the pellet mass deeper into the bulk plasma. In order to clarify this question, experiments have been conducted in ASDEX Upgrade where pellets were injected from both sides into H-mode plasmas and ε_f as well as pellet penetration depths were compared.

Experimental setup

Pellet fueling experiments are executed on ASDEX Upgrade (R_0 = 1.65 m, plasma radius a_0 = 0.5 m, V_{Plasma} = 13 m^3, b/a = 1.6; tungsten-coated divertor target plates) plasmas with lower single null configuration, I_P = 0.8 - 1.2 MA, B_t = 1.7 - 2.5 T, q_{95} = 2.7 - 4.2 and P_{NI} up to 7 MW for H^0 and up to 10 MW for D^0 injection. Pellet injection was performed either with a centrifuge injector or a blower gun. The centrifuge injected only from the LFS. D_2 pellets of variable velocity (240 to 1200 m/s) and mass (1.4 to 3.8 x 10^{20} particles) can be delivered at repetition rates of up to 80 Hz. The blower gun injects D_2 pellets containing 3 x 10^{20} particles, accelerated by H_2 gas flow up to 130 m/s at repetition rates of up to 17 Hz. Pellets are delivered via guiding tubes optionally from the magnetic low- or high-field side. Switching from one track to the other is possible within 60 ms.

Pellet ablation is monitored by a CCD camera and photodiodes. Video pictures showing the ablation zone of the pellets are used to estimate the pellet penetration depths. A DCN interferometer, a Li-beam system, a Thomson scattering system and an ECE radiometer are applied to measure the density profile and determine the plasma particle content; the latter two are also used for temperature profile investigations. The measured increase of the number of particles in the target plasma (1-5 ms after ablation) divided by the number of particles contained in the pellet is defined as fueling efficiency ε_f. To calculate ε_f we used the maximum pellet mass found in testbed shots.

Experimental comparison of LFS and HFS pellet refueling

To demonstrate the enhanced refueling performance of HFS pellets, LFS and HFS pellets were injected into the same plasma discharge under practically identical conditions. Fig. 1 shows the temporal evolution of such a discharge ($I_P = 0.8$ MA, $B_t = -1.9$ T, $q_{95} = 3.6$, $P_{NI} = 7.5$ MW). During the whole sequence the discharge maintained type-I ELMy H-mode behaviour. Gas puffing was initially applied to control the line-averaged density at the required value of 7×10^{19} m^{-3}. The LFS pellet injection sequence was started after the density reached the preprogrammed value, and the HFS sequence was applied about 0.5 s after termination of the LFS pellet sequence, when the discharge had returned to identical starting conditions. Both sequences consisted of a nominal 10 pellets each with the same, relatively small nominal velocity of 130 m/s. A strong enhancement of ε_f with the HFS pellets in relation to the LFS pellets can be concluded from the increase in line-averaged density. The ε_f with the HFS pellets are about 4 times as high as the values obtained for LFS pellets. The higher efficiency with HFS pellets is also obvious from the particle flux applied as D_2 gas puff. Pellets launched into the plasma are monitored by the spikes they cause in the D_α radiation. Reduced intensities observed with some pellets are most probably due to mass losses on the external pellet path. The time averaged particle flux of the nominal pellet sequence is shown as dashed line in fig. 1. Whereas additional gas input is required by the plasma control system during the LFS sequence to reach the preset line density, gas valves close almost immediately after the start of the HFS pellet train. The divertor neutral flux density Γ_0^{div} gradually increases during the LFS sequence, whereas an almost constant lower value is maintained during the HFS sequence. With HFS pellet injection, significant density increase is achieved without deterioration of the plasma energy or energy confinement time τ_E. With LFS pellet injection, in contrast, no comparable density increase is observed. In earlier LFS experiments [4], density enhancement similar to that with present HFS injection was achieved only with 80 Hz pellet injection yielding approximately 6 times higher particle flux. This enhancement was always accompanied by a loss of plasma energy, a reduction of τ_E and strong cooling of the plasma. Evolutions of according discharges refueled by pellets are compared to data obtained for gas

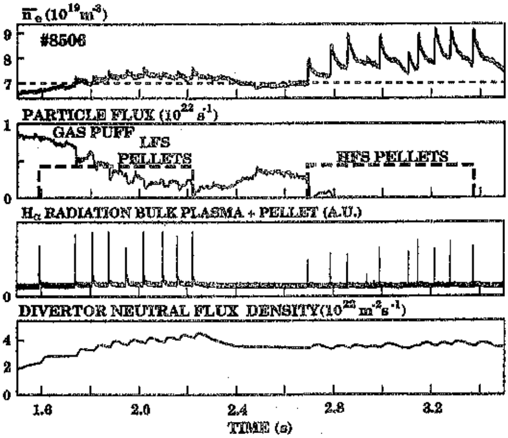

Figure 1: Temporal evolution of a discharge with LFS and HFS pellet injection applied performed with identical pellets and starting from almost identical plasma conditions.

puffed plasmas as shown in Fig.2. LFS pellet injection applying high particle flux to achieve high plasma densities causes a high neutral gas pressure P_{div} in the divertor. Increasing P_{div} however results, like in gas puffed discharges [5], in a degradation of the confinement. Reduced particle losses in the case of HFS injection allowed for a plasma density close to the Greenwald limit at lower divertor neutral pressure P_{div}, consequentely no significant confinement degradation occurs.

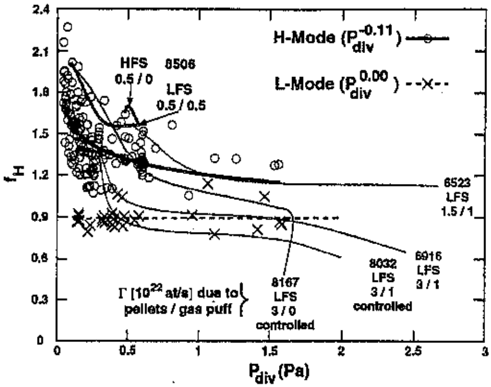

Figure 2: Enhancement factor f_H of energy confinement time relative to L-Mode scaling ITER89-P versus divertor pressure. Symbols and black curves: data for gas fueled discharges and according fits. Slim grey curves: evolution of LFS pellet refueled discharges to densities well above the Greenwald limit at different particle refueling flux rates. For LFS pellets, increasing plasma densities always are accompanied by high P_{div} and reduced f_H, whereas HFS injection (strong grey curve: evolution of #8506) approaches already $n_{e,Gw}$ at low P_{div} values without confinement degradation.

A series of pellet injections were performed under various plasma conditions to compare between LFS and HFS injection, Fig. 3 shows ε_f values for different P_{NI}. For P_{NI} > 5MW HFS pellets (filled symbols) showed efficiencies enhanced by up to four times that with equivalent LFS pellets (open symbols). With increasing P_{NI} and plasma temperature, HFS pellets show no significant power degradation of ε_f, whereas the maximum efficiency achieved using LFS pellets (solid line) is dropping. Even at the highest heating powers applied almost the same efficiencies are achieved for HFS pellets as in ohmic plasmas. The strong scatter of ε_f values is most probably an artefact caused by the external pellet mass losses mentioned earlier. This conclusion is further supported by the fact that reduced ε_f values were always accompanied by reduced ablation radiation. With the ablation radiation being assumed to be a good measure of the pellet mass [6], accordingly corrected ε_f values show a scatter reduced to ±10 % of the optimum value of ≈ 0.7 for the HFS pellets. For LFS pellets, however, a strong reduction in efficiency takes place despite the fact even bigger (3.8 x 10^{20} particles) and faster (1200 m/s) pellets were injected using the centrifuge at high heating powers, penetrating deep into the plasma. In the case of shallow penetration into type-I ELMy H-mode plasmas ε_f was even restricted to values below 0.2 [3]. Comparable conditions yielded the same result in the case of LFS pellet injection with the blower gun.

A striking difference in the pellet penetration depths Δ and ablation traces between LFS and HFS pellets became obvious from video observations. Whereas LFS penetration was rather low (Δ ≈ 8 cm for the discharge shown in Fig.1), significantly deeper penetration (Δ ≈ 19 cm) was found with HFS pellets. This strong difference cannot be wholly attributed to different local target plasma conditions or different flux tube spacings (Shafranov shift); we estimate that these effects yield an enhancement of with HFS pellets less than 1.6 times as large as the LFS values. Whereas LFS pellet penetration depths Δ are in agreement with published ablation scalings, HFS pellets were found to penetrate considerably deeper into the plasma. Obviously, an additional shielding mechanism must be responsible for the enhanced Δ of HFS pellets, which we attribute to the diamagnetic pellet plasma cloud drift.

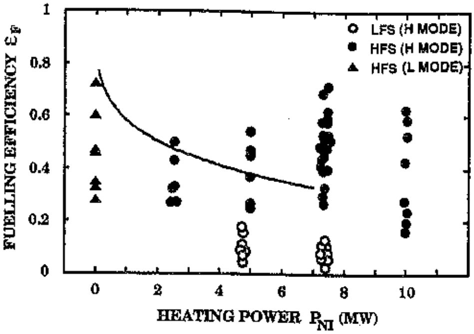

Figure 3: The triangles and circles show the fueling efficiency calculated on the assumption of maximum pellet masses versus additional heating power for LFS (open symbols) and HFS (filled symbols) pellets injected with the blower gun. Triangles: pellets into ohmic L-mode plasmas; circles: H-mode target plasmas. The solid line represents the upper limit of fueling efficiency in the case of LFS injection performed by the centrifuge.

Conclusions

Our experiments demonstrated that HFS pellet injection allows for efficient particle refueling of hot, high confinement plasmas relevant for next generation fusion experiments. The advantage over standard LFS injection seems to originate from the toroidal curvature, which tends to expell the diamagnetic ablation cloud from the LFS, while the same effect is highly beneficial for bulk refueling from the HFS.

References

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