COMPARISON OF CONFINEMENT IN HYDROGEN VERSUS DEUTERIUM IN MULTI-PELLET FUELLED OH DISCHARGES IN ASDEX

O. Gruber, M. Kaufmann, K. Lackner, R.S. Lang, V. Mertens, W. Sandmann, H. Murmann, F. Wagner, ASDEX Team

IPP Garching, EURATOM Association, Fed. Rep. of Germany

1. Introduction

In earlier investigations with multiple deuterium (D) pellet injection into ohmically heated D discharges (ASDEX tokamak, carbonized walls, I_p = 380 kA, B_t = 2.2 T, q^* = 2.7) a long-lasting period of peaked electron density profiles was obtained and the energy confinement time (τ_E) was increased by a factor of nearly two in relation to discharges with gas puffing (GP) only (see Fig. 1). The analysis of energy confinement [1] showed that during this high confinement phase ion energy transport is the dominant energy loss mechanism in the center ($r/a < 0.6$ cm) and revealed that the ion energy transport is neoclassical. Therefore, further improvement could be expected by changing from deuterium to hydrogen (H) if this situation were to hold. To investigate this question, the centrifugal pellet injector was modified to inject larger H and D pellets with 1.7×10^{20} atoms each, compared to 5×10^{19} atoms in the small D pellets. At the same velocity of 600 m/s the typical penetration depths increased from 20 ÷ 25 cm (small pellets) to 30 ÷ 35 cm (large pellets). We describe first the density build-up and particle transport and then we compare the bulk plasma energy transport of both H and D pellet refuelled discharges.

2. Density build-up and bulk plasma particle transport

With both D and H pellet injection a strong increase of the line-averaged ($\bar{n}_e$ up to $1.2 \times 10^{20} m^{-3}$) and volume-averaged ($< n_e >$ up to $8.5 \times 10^{20} m^{-3}$) densities could be obtained. This is accompanied by a strong peaking of the density profiles with $n_e(o)/ < n_e >$-values up to 2.5 compared with 1.3 ÷ 1.5 for the GP phase. During this peaking the electron temperature (T_e) drops but the T_e-profile shape stays nearly self-similar ($T_e(o)/ < T_e > \approx 1.9$). This is shown in Fig. 2 where the time development of n_e and T_e are given for a discharge with large H pellets measured by Thomson scattering with a 16 channel YAG laser system, providing data very 17 ms. The measured data points are smoothed between adjacent pellet pop times and extrapolated to them. The peaked density profiles remain nearly stationary for times up to 230 ms (D) and 150 ms (H), respectively.

These strong density increase and profile peaking originate from 3 effects. Firstly, a fast transport process (time scale $< 1ms$) can produce both a decrease of $T_e(o)$ - keeping the temperature profile self-similar - and an increase of $n_e(o)$ immediately after the pellet injection despite of the penetration depth being smaller than the plasma radius a. Secondly, reduced sawtooth activity leads to a n_e-profile peaking due to the omission of an instantaneous particle outward flow during a sawtooth disruption. From the nearly stationary and source-free density profiles of GP D plasmas one can deduce the ratio of an inward velocity V_D and the particle diffusion coefficient D_p by $V_D/D_p = -dn/dr/n$ which is increasing from $V_D/D_p = r/a^2$ (time averaged) with sawteeth to 3.5 r/a^2 in a sawtooth free discharge. Only D discharges tend to loose sawteeth. Finally, reduced D_p or increased V_D values are observed during and after the pellet injection phases, where a V_D/D_p up to 5.5 r/a^2 can yield a further n_e profile peaking [1]. With large H and D pellets the first effect seems to dominate during the peaking phase, but is certainly subsidized by the larger penetration (see Fig. 2a). The last two effects are the predominant cause for the peaking in the case of small D pellets and for the nearly stationary post pellet phases [1].

During the density build-up central radiation increases drastically. This results from the high $n_e(o)$ and from the increase of highly ionized metal impurities. While the total losses remain below 40 % of the ohmic input power, the radiation loss dominates the central power balance and internal disruptions occur strongly reducing energy and particle content. Z_{eff} obtained from absolute bremsstrahlung measurements and the loop voltage using neoclassical resistivity shows no peaking (the contribution due to the metal impurities is less than 0.1).

3. Energy confinement

H and D discharges with GP fuelling only show the roll-over from the linear dependence $\tau_E \sim \bar{n}_e$ to a saturated τ_E regime beyond $\bar{n}_e \approx 3 \times 10^{19} m^{-3}$. In the saturation region with "broad" density profiles $(n_e(o)/ < n_e >= 1.3 \div 1.5)$ the known reduction of energy confinement of H discharges ($\tau_E \approx 60 \div 70ms$) in relation to D discharges ($\tau_E \approx 80 \div 90ms$) holds. In the pellet discharges with successful density build-up and peaking the τ_E's could be improved to 110 ms (H) and 160 ms (D) at the same discharge conditions (see Fig. 1).

This suggests that the pellets remove the reason for the roll-over which can be explained by two alternatives. A profile consistency picture with fixed $T_e(r)/T_e(o)$ depending only on q yields a τ_E saturation in GP discharges from a decrease of $T_e(o)$ and an increase of ohmic dissipation, whereas the pellet discharges gain in τ_E due to a more favourable weighting of $T_e(r)/T_e(o)$ with the high $n_e(o)$ values [1]. A "local" model for conductive energy transport was investigated with the TRANSP code. To describe the τ_E saturation we have to add to the neo-classical ion energy losses as given by CHANG-HINTON, χ_{CH}, and to an anomalous electron heat conductivity, χ_e, an additional heat conduction channel causing the τ_E saturation. CX measurements of T_i, measured β_p and neutron productions guide as to describe this loss channel as an ion loss resulting in a $\chi_i \approx (3 \div 4) \times \chi_{CH}$ and a $\chi_e \sim 1/(n_e T_e q)$. During the discharge phases with strongly peaked density profiles the effect causing the ion transport enhancement has to be quenched: $\chi_i > \chi_{CH}$ would require an electron heat transport toward the plasma center against ∇T_e in order to satisfy the power balance. With neo-classical ion losses $(\chi_i = \chi_{CH})$ during this pellet phases, however, GP and pellet results can be brought well into line with a continuous explanation of electron losses through $\chi_e \sim 1/(n_e T_e)$ (fixed q).

The Alcator team has suggested first to attribute this additional ion loss to the ion temperature gradient mode triggered when the criterion $\eta_i = dlnT_i/dlnn_i = L_{n_i}/L_{T_i} > 1.5$ is fulfilled [2]. Figure 3a shows that due to the n_e peaking $\eta_i \approx \eta_e$ ($T_i \approx T_e$ at high $\bar{n}_e$)

decreases from above 1.8 at all radii in the GP phase to values below 1 over a large part of the plasma cross-section. Using a $\chi_i = \chi_{CH} + \chi_{\eta i}$ with $\chi_{\eta i} = 0$ for $\eta_i < 1$ and fully developed for $\eta_i \geq 1.8$ [3] the time development given in Fig. 3c for the i and e heat diffusivities at r/a = 2/3 of a H pellet discharge are obtained. While χ_e is only slightly decreasing with time, χ_i drops immediately after the first pellet from $(3 \div 4)\chi_{NC}$ to χ_{NC}. This model assumption is further supported by two facts. τ_E is at once improved when already the first pellet reduces η_i to 1 (as is the case given in Fig. 3), but is only gradually rising when the n_e-peaking and η_i reduction occur more slowly which happens especially with small pellets. Secondly the confinement improvement is only marginal when the $\eta_i < 1$ region is small.

The neoclassical ion loss in the high confinement pellet regime accounts still for the major part of the total non-radiated power flow within half the plasma radius. But the global energy confinement is governed by the anomalous electron heat transport in the outer plasma region with $\chi_e >> \chi_i$. As χ_{NC} is the upper bound for χ_i one can calculate the radial dependence of χ_e. Figure 4 compares χ_{CH} and χ_e both for a H and D post pellet phase at the same $q^* = 2.7$, having about equal T_e profiles and the same n_e profile shape. The χ_i's differ by the $\chi_{NC} \sim \sqrt{A_i}$ dependence (ion mass A_i), whereas $\chi_e(H)$ clearly exceeds $\chi_e(D)$. Taking into account the higher density of the D discharge a $\chi_e \sim A_i^{-\alpha}$ with $\alpha = 0.3 \div 0.7$ can be extracted; explaining also the inferior energy confinement times of H pellet discharges.

4. Summary

H and D ohmic heated pellet discharges show a density build-up (beyond the GP density limit) with strongly peaked n_e profiles $(n_e(o)/ < n_e > \leq 2.5)$. They show in parallel a remarkable improvement of energy confinement by nearly a factor of two. With these peaked density profiles χ_i is restricted to χ_{CH}. This allows a determination of $\chi_e \sim A_i^{-\alpha} (\alpha \approx 0.5)$ dominating the global energy confinement and reducing $\tau_E(D) \approx$ 160 ms to $\tau_E(H) \approx 110$ ms.

References

[1] M. Kaufmann, et al., IPP-Report 1/242, to be published in Nucl. Fusion.

[2] G.S. Lee, P.H. Diamond, Phys. Fluids **29**, 3291 (1986).

[3] O. Gruber, et al., this conference.

Figure Captions

Fig. 1: Energy confinement time τ_E vs. $\bar{n}_e$ for GP (points) and pellet fuelled hydrogen (H) and deuterium (D) single ohmic discharges.

Fig. 2: Axial (r=o) and volume averaged (<>) n_e and T_e vs. time for a hydrogen pellet discharge (points are measured by Thomson scattering).

Fig. 3: a) $\eta_e = dlnT_e/dlnn_e$ at three radial positions,
b) τ_E, electron (τ_{Ee}) and ion (τ_{Ei}) confinement times and
c) χ_e, χ_i and χ_{CH} at r/a = 2/3 as a function of time for the discharge of Fig. 2.

Fig. 4: Radial dependence of χ_e and χ_i during post-pellet phase of a H and D ohmic discharge.

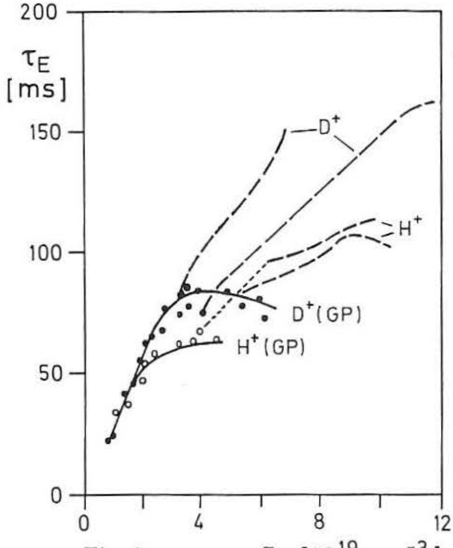

Fig. 1

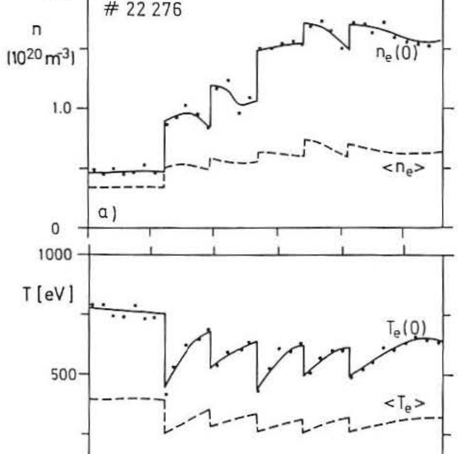

Fig. 2

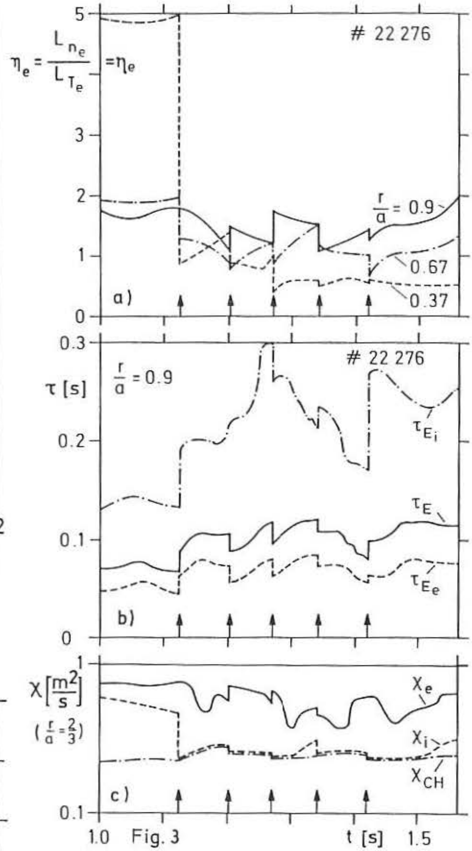

Fig. 3

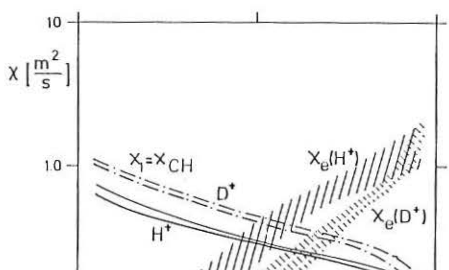

Fig. 4