INFLUENCE OF DENSITY PROFILE SHAPE ON PLASMA TRANSPORT IN ASDEX

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1. Introduction

In ASDEX divertor discharges we observe - besides the H-mode - four regimes of long lasting improved energy and particle confinement compared with gas-fuelled (GP) ohmic (OH) and co-beam heated plasmas, namely OH and beam heated pellet refuelled discharges [1, 2], OH discharges without sawteeth, discharges with neutral injection in the counter direction (ctr-NI) [3] and ohmic discharges near the density limit with reduced gas-puff (GP) [4]. All these discharges have strongly peaked density profiles with ratios of the axial ($n_e(0)$) to the volume averaged ($< n_e >$) electron density of up to 2.5 compared with $1.4 \div 1.6$ of the other discharge types. During the density increase to line-averaged values ($\bar{n}_e$) of up to $1.2 \cdot 10^{20} m^{-3}$ the electron temperature (T_e) profile shape stays nearly self-similar depending only on q_a. Good particle confinement and high $n_e(0)$ lead to high-Z impurity accumulation and high central radiation losses, which can dominate the central power balance and can give rise to hollow T_e-profiles and internal disruptions in a final phase. The tendency toward the observed reduced sawtooth activity may be a further result. Z_{eff} increases owing to light impurities.

According to theory peaked density profiles may lead to reduced anomalous heat transport if the threshold condition of the trapped electron or ion temperature gradient modes, namely $\eta_{e,i} = d\ell n T_{e,i}/d\ell n n_e = L_{n_e}/L_{T_{e,i}} \geq \eta_c \approx 1.5$, is not violated [5]. The measured η_e and - as $T_i \approx T_e$ at the high $\bar{n}_e$'s $-\eta_i$ values of the high confinement discharges indeed decrease to values below 1 over a large part of the plasma radius (see Fig. 3a, [1]). An alternative explanation follows the profile consistency model. According to it, $T_e(r)/T_e(0)$ in the bulk of the plasma is fixed by stability restrictions, whereas the normalization constant is determined by local transport processes in a near-boundary zone. The roll-over of $\tau_E(\bar{n}_e)$ in GP OH discharges follows then from a decrease of $T_e(0)$ with density and the concomitant increase in ohmic dissipation, whereas the high confinement discharges gain in τ_E from a more favourable weighting of $T_e(r)/T_e(0)$ with the peaked density profiles.

In this paper we try to identify the dominating energy loss channels using the TRANSP analysis code and measured plasma parameters: n_e, T_e, T_i and radiation profiles and global parameters (loop voltage, Z_{eff}, β_{pol}).

2. Gas-fuelled OH and co-beam heated discharges

In ASDEX we observe "broad" density profiles with $n_e(o)/ < n_e > \approx 1.4 \div 1.6$ and $\eta_{e,i} > 1$ at all radii in gas-fuelled ohmic and co-beam heated plasmas at q-values around 3. OH discharges show the roll-over from the linear dependence $\tau_E \sim \bar{n}_e$ to a saturated τ_E regime beyond $\bar{n}_e \approx 3 \cdot 10^{19} m^{-3}$. Confinement is degraded in the additionally heated L-mode plasmas and improves again in the H-mode even at high heating powers. In all three regimes a reduction of τ_E of hydrogen (H^+) discharges in comparison with deuterium (D^+) discharges holds. To describe the observed confinement we have to add to an anomalous electron heat conduction channel and to the neo-classical ion energy losses as given by Chang-Hinton, χ_{CH}, an additional heat conductiviy contribution causing for instance the saturation of ohmic confinement at high densities. CX measurements of T_i, measured β_p and neutron productions can be described consistently when we assume enhanced ion losses with an enhancement factor of $\chi_i = (3 \div 4)\chi_{CH}$ over the neoclassical value.

This brings low and high density OH results into line with a $\chi_e(OH) \sim 1/(nT_eq)$ [1], dominating at low densities the power balance. We have started to simulate the ion losses by a $\chi_i = \chi_{CH} + \chi_{\eta_i}$ [5] with $\chi_{\eta_i} = o$ for $\eta_i \leq 1$ and fully developed for $\eta_i \geq 1.8$ including an enhanced threshold for the long density decay length (L_{n_e}) region. Figure 1 shows for a GP ohmic discharge that χ_{η_i} yields obviously the necessary χ_i enhancement, and η_i, which is smaller than η_e, is clamped to values between 1 and 2. Electron and ion heat conduction losses (P_{ce}, P_{ci}) are about the same at this medium density. The η-modes have, however, in their present theoretical form the wrong dependence on the ion mass A_i (χ_η is increasing with A_i) to explain the observed isotope dependence of τ_E. This discrepancy may be explained by the more peaked density and broader T_i profiles of the D^+ plasmas compared with those of the H^+ plasmas at nearly the same T_e shape yielding $\eta_i(D^+) < \eta_i(H^+)$ and $\chi_{\eta_i}(D^+) < \chi_{\eta_i}(H^+)$.

In L-mode discharges P_{ce} exceeds P_{ci} and $\chi_e(L) > \chi_e(OH)$ holds at the same $\bar{n}_e$ and increased temperatures. This can be seen by comparing Fig. 1 and Fig. 2, which shows the analysis results for a H° beam heated D^+ discharge. Only an $\chi_i > \chi_{CH}$ can explain the T_i measurements, whereas a $\chi_i = \chi_{CH}$ would yield too high T_i values.

3. Pellet fuelled discharges

Ohmic and co-beam heated pellet-fuelled discharges with strong density profile peaking exhibit a confinement improvement compared with GP fuelled discharges (doubling of τ_E) [1, 2]. In the OH pellet discharges with a density peaking of $n_e(o)/ < n_e >$ up to 2.5 the reason for the roll-over of τ_E is removed and the effect causing the ion transport enhancement has to be quenched: $\chi_i > \chi_{CH}$ would require an electron heat transport against ∇T_e in order to satisfy the power balance. With $\chi_i = \chi_{CH}$ during these pellet phases, however, a $\chi_e \sim 1/(nT_e)$ at fixed q results again. Global confinement is then governed by the electron heat transport. The confinement times for D^+ (≤ 160 ms) exceed those for H^+ (≤ 110 ms) considerably and a $\chi_e \sim A_i^{-\alpha}$ with $\alpha = 0.3 \div 0.7$ can be deduced [1].

4. Ctr-beam heated discharges

Ctr-injection in ASDEX leads to a doubling of $\Delta\beta_p$ due to NI compared with a comparable co-injection discharge and an improvement of τ_E up to 80 ms [3]. Confinement is gradually improving along with a continuously peaking of n_e yielding $n_e(o)$ above $1 \cdot 10^{20} m^{-3}$ and a peaking factor $n_e(o)/ < n_e >$ up to 1.9. The T_e profile shape changes mainly in the central part, where it becomes hollow due to increasing radiation losses. η_e and the calculated η_i values are below 1 over 2/3 of the plasma radius (see Fig. 3a).

Again as in the pellet discharges $\chi_i = \chi_{CH}$ has to be assumed: with $\chi_i > \chi_{CH}$ the energy content of the plasma is underestimated even in the extreme of no additional electron transport. In this situation the neoclassical ion losses dominate over the electron heat losses ($T_i \approx T_e$). χ_e (see Fig. 3b) is strongly decreased compared with that of the co-NI case shown in Fig. 2, having nearly the same plasma current, but a somewhat higher heating power. Along with the improvement of the energy and particle confinement also the one of momentum is observed to increase with ctr-NI. The plasma rotation velocity is measured outside a/2; it increases throughout the ctr-beam phase up to $v_\phi(\frac{a}{2}) \simeq 1.5 \cdot 10^5 m/s$. Assuming a $v_\phi \sim (1 - r^2/a^2)^{1.3}$ the momentum confinement time at the end of the ctr-phase is $\tau_\phi = 90ms$ and the momentum diffusivity is comparable to the electron heat diffusivity.

5. Summary

There are 4 regimes with peaked density profiles at ASDEX: pellet refuelled and ctr-NI discharges, OH discharges without sawteeth and those with reduced GP. The reason for the development of the peaked density profiles may be quite different and is not yet understood in all cases. But all regions have improved confinement which is partly offset by core radiation. Transport analysis - only performed for the first two regimes up to now - reveals that the ion transport has to be reduced in comparison to the broad density profile cases (OH-saturation and co-NI L and H-mode). η_i-modes may explain this result. Interestingly, in the small tokamak Pulsator the η_i-values are below 1 and the ion transport was consistently observed to be neoclassical.

References

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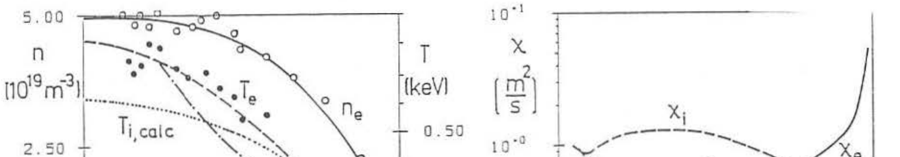


Fig. 1: Radial profiles for a OH discharge ($I_p = 380kA$, $B_t = 2.2T; \bar{n}_e = 4 \cdot 10^{19} m^{-3}$);
a) $T_e(o)$ and $n_e(o)$ from Thomson scattering, η_e and T_i (calc. using $\chi_i = \chi_{NC} + \chi_{\eta_i}$);
b) transport coefficients from TRANSP analysis.

Fig. 2: Radial profiles for a co-NI L-mode discharge ($I_p = 440kA; B_t = 2.3T$; $\bar{n}_e = 4.5 \cdot 10^{19} m^{-3}, P_{NI} = 1.35MW$);
a) $T_e, T_i(o)$ from pass. CX-meas., η_e, T_i (using $\chi_i = \chi_{NC} + \chi_{\eta_i}$) and T_i ($\chi_i = \chi_{NC}$);
b) transport coefficients from TRANSP analysis.

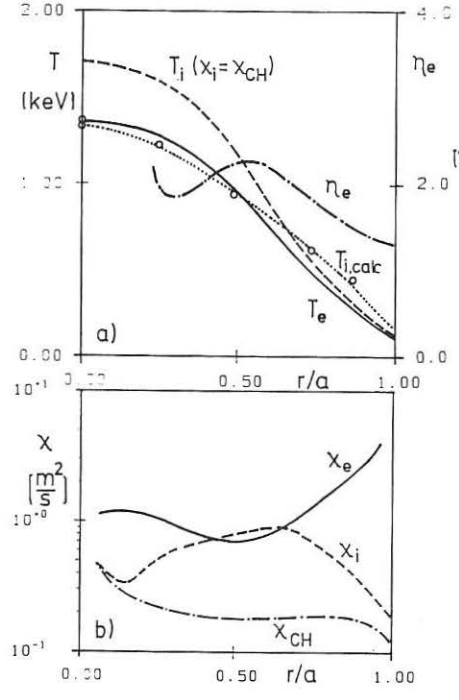
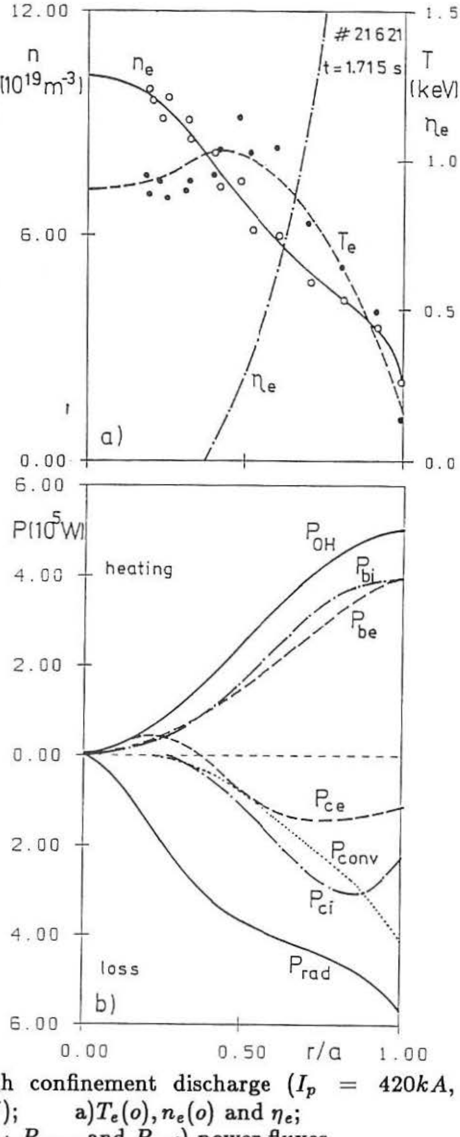


Fig. 2



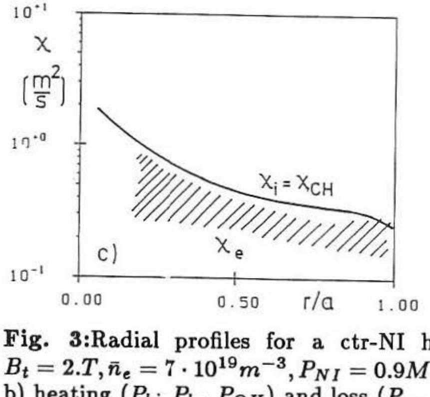


Fig. 3:Radial profiles for a ctr-NI high confinement discharge ($I_p = 420kA$, $B_t = 2.T, \bar{n}_e = 7 \cdot 10^{19} m^{-3}, P_{NI} = 0.9MW$); a) $T_e(o), n_e(o)$ and η_e;
b) heating (P_{bi}, P_{be}, P_{OH}) and loss (P_{ce}, P_{ci}, P_{conv} and P_{rad}) power fluxes.
c) $\chi_i = \chi_{CH}$ and χ_e from TrANSP analysis.