CONFINEMENT STUDIES ON ASDEX IN THE INTERMEDIATE REGION FROM OHMIC TO NEUTRAL INJECTION SCALING

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Abstract: The scaling of the global energy confinement time with density and plasma current is studied in the intermediate region from Ohmic to neutral injection L-scaling with beam power $P_{NI} \sim (1 - 3) \times P_{OH}$. A gradual transition from Ohmic to neutral injection L-scaling is found. The results can be described by quadratically adding the Ohmic- and L-scaling characteristics indicating that the L-scaling may be the continuation of Ohmic scaling towards higher power and that non-local properties determine the transport.

Introduction: The global energy confinement time τ_E of Ohmic (OH) discharges increases linearly with density at low density and saturates towards higher densities /1/. In the linear range, τ_E increases with safety factor q_a while it decreases with q_a in the saturation region /2/. In neutral injection (NI) heated L-discharges with degraded global confinement, τ_E does not show any density dependence but increases linearly with plasma current I_p in the limit $P_{NI} \gg P_{OH}$ /3/.

Results: Figure 1 and 2 summarize the scaling results obtained in ASDEX in the transition regime $P_{NI} \sim P_{OH}$. Plotted is τ_E (deduced from a carefully compensated diamagnetic loop) versus density (Fig. 1a, b for a D^+ and Fig. 2 for an H^+ plasma) for low and high q_a and versus plasma current (Fig. 1c, d) for low and high density. The injection isotope is hydrogen.

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Ohmic phase: The data of Fig. 1a, b and Fig. 2 show both the linear region where $\tau_E \alpha \bar{n}_e$ and the saturation region where τ_E is rather independent of density. The comparison of low- and high-q_a-cases of Fig. 1a and b confirms the previously reported fact that the confinement improves with q_a in the linear range but decreases with it in the saturation range /2/. A comparison of the results shown in Fig. 1a and 2 reveals that the Ohmic τ_E-values are about the same in the linear range but differ in the saturation regime with $\tau_E{}^D/\tau_E{}^H = 1.3 - 1.5$. The result that the isotope mass affects τ_E only in the saturation regime may clarify the conflicting observations: Those tokamaks which operate predominantly in the linear range (small minor radius or low B_T/R_o) do not observe an isotope effect while clean divertor tokamaks which can run at high density and generally operate in the saturation region do.

Neutral injection phase: The net effect of NI is a general decrease of τ_E with beam power (L-regime). At low density, however, the τ_E-values with one NI-source are comparable to (or even above) the Ohmic values and at high density they seem to continue the variation of the Ohmic data towards higher densities (see Fig. 1a). This deviant behavior at the edges of the density range may be attributed to the ion confinement: At low density, in the limit of $T_i \gg T_e$, τ_E approaches $\tau_{ei} \cdot P_i/P_{NI}$ (τ_{ei} is the electron-ion euqilibration time, and P_i/P_{NI} is the beam power fraction directly transferred to the ions). Decisive beam contributions to β_p at low density enhancing τ_E can be ruled out. At high density, the confinement is determined by neoclassical ion heat conduction, which does not seem to degrade with beam heating /4/. The density dependence of τ_E vanishes gradually with beam power. At $P_{NI} = 0.45$ MW, the linear and saturation regions are still discernible, and the maximum in τ_E is shifted to higher density. At $P_{NI} = 1.32$ MW there is still a slight density dependence. The increased power, however, has enhanced the electron transport to such an extent that the ion transport does not play any role in the given density range and the OH τ_E-values are no longer attained (Fig. 1a). At high q_a (low plasma current), NI causes a loss of density dependence even at low beam power (Fig. 1b). This is partly due to the small density window accessible at high q_a. On the other hand, the q_a-enhancement of the OH values in the linear density range is easily offset because NI confinement favors high current. This is also shown by the current scaling of high density discharges (Fig. 1d) while the high current τ_E-values are hardly affected at low density (Fig. 1c). Both the low and high density runs show the gradual transition into the linear I_p-scaling with NI.

Discussion: The degradation in confinement occurs both in the low density linear region but is more pronounced in the saturation region. The local transport analysis in the insulation zone, the density fall-off length in the scrape-off layer and the rise of the electron energy density in the plasma center after a sawtooth event indicate enhanced transport with NI over the whole plasma cross-section. It appears that the plasma is forced to locally adjust its transport properties.

It has been observed before /5/ that the electron temperature (and consequently the current density j) shows a remarkable profile conservation (termed profile consistency /6/) during beam heating. This property applies also to the density scans of Fig. 1a: The central electron temperature varies by a factor of 3 from 0.55 keV (high density, OH) to 1.8 keV (low density $P_{NI} = 1.32$ MW) while the T_e profile parameter $\alpha (T_e = T_{eo} (1-\rho^2)^{\alpha})$ scatters between 1.1 and 1.5. It appears that Ohmic heating conditions which link power deposition and the j-profile (Ohmic constraint) give rise to an optimal j-profile (e.g. due to the stability condition of macroscopic modes) yielding low transport. With the independent power deposition profiles of neutral injection, the plasma maintains the optimal current density profile by changing its transport properties. Peaked deposition causes a general rise in the thermal diffusivity χ_e but low beam energy, off-axis deposition yields a remarkable reduction of χ_e in the plasma core /7/.

The possible dependence of χ_e not only on local parameters but also on a global consistency condition encouraged Goldston to quadratically add the Ohmic $\bar{n}_e q_a^{1/2}$-scaling and the NI I_p-scaling which yielded a heuristic description of the saturation region of Ohmic confinement /5/. We have analyzed the scaling results presented here according to $\tau_E^{-2} = (\tau_E^{OH})^{-2} + (\tau_E^{NI})^{-2}$ (equ. 1) with $\tau_E^{OH} = C_1 \bar{n}_e q_a^{0.5}$ and $\tau_E^{NI} = C_2 I_p P_{NI}^{-0.6}$. The coefficients C_1 and C_2 are obtained from fitting the OH-curve of Fig. 1a; the power dependence of τ_E^{NI} is chosen according to the L-regime scaling at low beam power /3/. The dashed lines in Fig. 1a-d represent the calculated values putting experimental data of $\bar{n}_e$, I_p and the total OH and NI power into relation (1). Good agreement is found which indicates that non-local conditions (like profile effects) may affect confinement and that the L-regime of beam heated plasmas is the continuation of an OH scaling porperty to larger heating power. On the other hand, the saturation region of OH ASDEX plasmas can be explained by neoclassical ion transport /8/. The observed isotope dependence, however, which is common to both the OH saturation region and the L-scaling does not agree with neoclassical ion transport. It has to be tested whether the different scaling relations can be reconciled incorporating the ion transport in the form $\tau_E^{-1} = (\tau_E^{OH})^{-1} + (\tau_{Ei}^{NI})^{-1} + (\tau_E^{NI})^{-1}$

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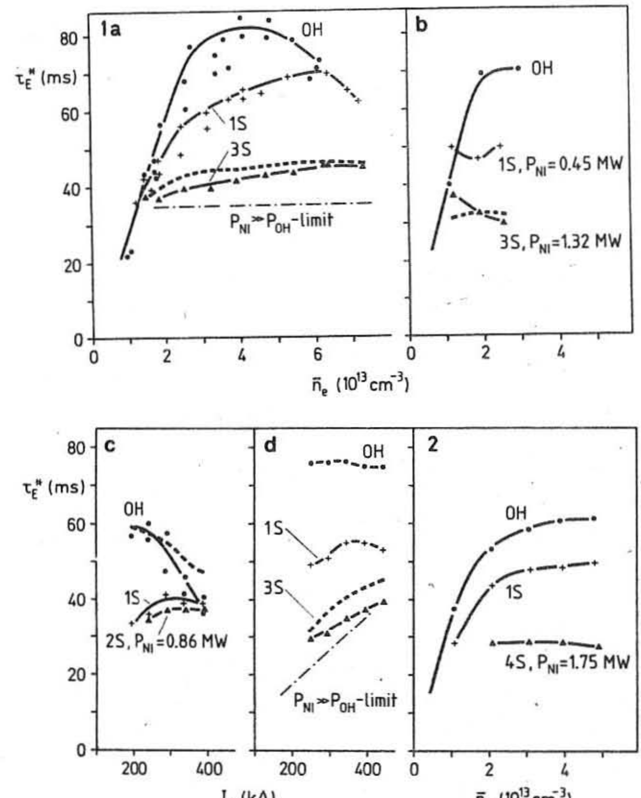

Fig. 1: Density and current scaling of the global energy confinement time of deuterium discharges. S = number of NI-sources
a) I_p = 0.4 MA, B_T = 2.2 T, q_a = 2.6; (b) I_p = 0.25 MA, q_a = 4.2;
c) $\bar{n}_e = 1.7 \cdot 10^{13}$ cm^{-3}, B_T = 2.2 T; (d) $\bar{n}_e = 3.3 \cdot 10^{13}$ cm^{-3}.

Fig. 2: Density scaling of hydrogen discharges. I_p = 0.4 MA, B_T = 2.2 T.