Role of recycling to achieve high $nT\tau_E$ in W7-AS

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Introduction High $nT\tau_E$ at W7-AS in pure or combined NBI and ECRH discharges is only obtained for low edge density. In the case of combined heating, steep temperature gradients (T_e' as well as T_i') in the region of low densities in connection with strongly negative radial electric fields are observed [1]. In the bulk plasma, both energy balances (electrons and ions) and particle balance are in good agreement with the neoclassical fluxes. In the gradient region the particle fluxes are still anomalous, but are much lower than in discharges with higher edge densities and lower confinement. Central values of high confinement plasmas with e. g. 825 kW NBI and 370 kW ECRH absorbed power are $n_e = 1 \cdot 10^{20}$ m^{-3}, $T_i = 1$ keV and $\tau_E \approx 22$ ms. This is by a factor of about 2 larger than the one from the International Stellarator Scaling [2].

The same relation between confinement and profile characteristics appears if one considers the dependence of confinement on rotational transform ι or density in W7-AS. The variation of the latter leads partly to remarkable transitions in confinement. This points to a crucial dependence of global confinement quality, edge profiles and recycling.

Particle Transport The influence of recycling and particle transport is studied in ECRH deuterium discharges with moderate heating power (≈450 kW) where either ι or the averaged line density was varied between shots. In addition, discharges with a density ramp were performed and these are discussed in the next section. The plasmas were limiter bounded ($B_z = 23$mT) by the symmetric inboard limiters [3], which allows particle transport analysis with defined sources. ι was in the range around 1/3, which shows a resonance-like dependence of confinement and ι in W7-AS (upper part of Fig. 1) [4]. At first sight this behaviour might indicate a *direct* influence of magnetic islands on transport, but neither this nor MHD activity seem to explain the observations. Possible explanations are given on the basis of anomalous transport effects induced by rational ι-surfaces and/or ι-shear [5-7]. The H_α-signal (lower part of Fig. 1), which roughly corresponds to the particle flux at the edge, shows a strong anti-correlation to W_{dia}. This means that the particle transport is very important in this resonant phenomenon.

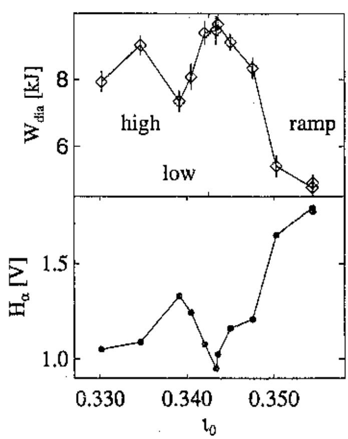

Fig. 1: Diamagnetic energy W_{dia} and H_α-signal at the inboard limiter vs. central ι_0. The shadowed lines mark the ι_0-values of the discussed discharges with low or high confinement and density ramps.

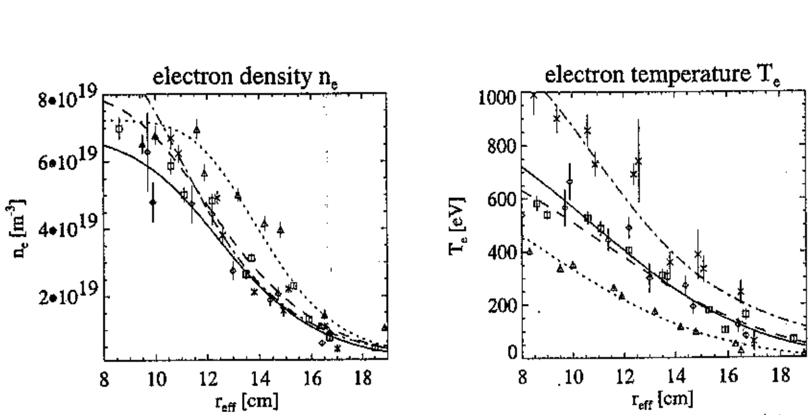

Fig. 2: Plasma profiles in the gradient region for low and high confinement. Below (#29925, solid line, ◇) and above (#29927, dotted, △) density threshold at $\iota_0 = 0.338$. At $\iota_0 = 0.335$ (#29928, dashed, □). High $nT\tau_E$ NBI discharge (#34609, dash dot, ×). Explanation see text.

Besides ι the density has an equivalent influence on confinement. This can be shown as follows: if at $\iota_0 = 0.338$ the line density is increased the confinement suddenly decreases at a certain density. Fig. 2 shows the profiles near the confinement transition. Above the density threshold the density at the limiter increases and the density profile broadens; also the particle edge flux (H_α) increases. Simultaneously the temperature significantly lowers over the entire plasma radius and as a consequence the energy content decreases by almost 20%. If then ι is decreased to a high confinement value ($\iota_0 = 0.335$, same line density), the former state with a narrow density profile and good confinement is re-established. Therefore at this point a slight change in ι or n_e have the identical effect. The comparison with the high confinement NBI heated discharge shows a nearly identical density profile at the edge ($r_{eff} \geq 12$cm) although the central density is almost twice as high. So low edge densities seem to be a necessary condition for obtaining high confinement.

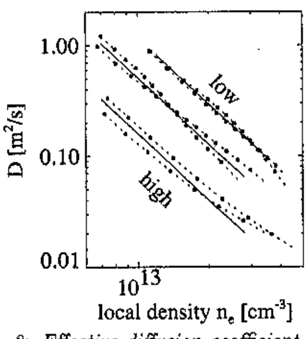

Fig. 3: Effective diffusion coefficient D vs. local density. Given are the "experimental" radial D's between $r_{eff} = 12$ and 17 cm for discharges (dots, dashed) of low (e. g. #29927) and high (e. g. #34609) confinement and between them (#29925,#29928). The lines are rough fits to $(cn_e)^{-2}$ with $c \cdot 10^{13} = 0.92, 1.4, 2.5$ from low to high confinement.

The particle transport is investigated with the help of the 3D Monte-Carlo code EIRENE [8], which provides the particle sources. The adaption to the experimental conditions was done with a similar procedure as formerly [9]. From a radial 1D diffusion equation (n_e-distribution in cylindrical symmetry) radially resolved particle fluxes and an effective diffusion coefficient are obtained. In fig. 3 the diffusion coefficients D of the discharges of fig. 2 are shown. It clearly can be seen that the relative density dependence is the same for all types of confinement. The n_e^{-2}-dependence found here is in contrast to earlier observations, which scale with n_e^{-1} [10], but the discrepancy is not understood so far. However the absolute value of D differs according to the quality of confinement: better confinement means lower D. The same applies to the edge particle flux, which in the high $nT\tau_E$ NBI discharges with $\sim 10^{21}$ part/s is very low compared to $\sim 5 \cdot 10^{21}$ part/s in the low confinement case. A more astonishing point is that the differences in D can be resolved, if the local T_e is also taken into account. Then the diffusivities can be described by $D \sim (n_e T_e)^{-1}$. However the implication is not clear: there could e. g. exist a mechanism, which acts both on n_e and T_e profiles, or there is some direct relation between energy and particle transport. Therefore it should carefully be interpreted as some additional parameter whose value effects D.

Density ramps In order to investigate the dynamic behaviour of the confinement transition, discharges with positive and negative density ramps were performed. In fig. 4 the difference of a density ramp discharge with low and high confinement is shown. While in high confinement the energy content increases linearly with density, in the other case the diamagnetic energy deteriorates above the density threshold again. Both energy loss and edge flux are increased by a factor of 2 compared to high confinement. Due to the excellent wall conditions the typical time scale of a density ramp-up ($\sim$0.5s) could also be obtained in ramp-down discharges. Since in both cases the transition occurs at the same line density, the density can be clearly identified as the transition parameter. Fig. 5 shows a discharge with a density ramp-down at low confinement $\iota_0 \approx 0.354$ (see fig. 1). It exhibits a very sharp transition to high confinement as the density decreases. This can be seen especially in the edge flux (H_α), which drops on a ms-scale, but also in n_e- and T_e-profiles. After the transition the profiles evolve over 150 ms until a new quasi-stationary state is formed. The energy content increases (due to T_e) up to the value, which is observed in an equivalent discharge at high confinement ι. At the same time the density profile at the edge stays nearly constant, but the line density still decreases. This indicates the change of the density profile shape. The transition is not always as fast as in Fig. 5. A higher wall recycling e. g. smoothes the transition, because it influences the edge density profile.

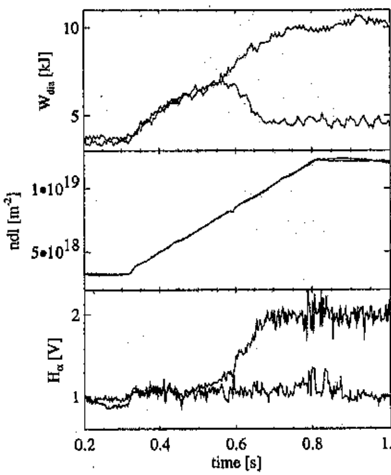

Fig. 4: Density ramp-up for two different ι at low ($\iota_0 = 0.354$) and high ($\iota_0 = 0.344$) confinement. In the low conf. case the edge flux (H_α) increases with the confinement decrease, whereas in the other case the particle confinement stays constant.

From the data, no clear causality between the influence of n_e and T_e can be drawn. At the transition the edge n_e-profile (by Li-beam) decreases, which marks the lower edge density with better confinement. Simultaneously the particle flux is reduced, which corresponds to the lower D in high confinement (see fig. 3). Also the sudden increase of T_e as well as the increased negative radial E-field (v_{pol}) indicate the better confinement.

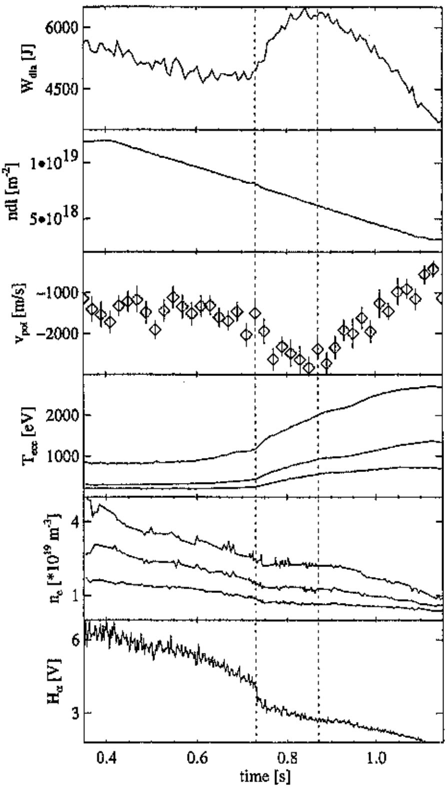

Fig. 5: Time evolution of discharge #39258 ($t_0 =$ 0.354) with a negative density ramp. Shown are from top to bottom: diamagnetic energy, central line density from microwave interferometry (line of sight = 50 cm), pol. rotation speed (by CXRS), T_e by ECE at $r_{eff} = 1, 7, 10 cm$, n_e by Li-beam at $r_{eff} = 12, 14, 16 cm$, H_α-signal at the inboard limiter. The transition occurs at 0.73s; only after 150ms the energy content reaches its maximum.

To elucidate the relation between particle flux and the edge density, the radial diffusion equation in cylindrical coordinates has been solved. For the diffusion coefficient typical "experimental" diffusivities as shown in fig. 3 were used. The simple $\frac{1}{n^2}$-dependence can reproduce broad and narrow density profiles similar to the experimental ones. However the edge fluxes were about 10% higher in the case of a narrow profile. It was not possible without additional assumptions to bring down the fluxes as found in the experiment. This corresponds to the observation of the last section, that a $D = D(n_e)$ description is not sufficient to explain the different particle confinement.

Conclusions A low edge density seems to be a prerequisite for high confinement in W7-AS. This applies also to the resonance-like dependence of confinement with ι. The strong anti-correlation of edge fluxes and W_{dia} shows the close connection of particle transport and this resonant phenomenon. There exists a density threshold, where a fast transition of confinement occurs. The particle transport analysis of different confinement states gives to the known n_e-dependence an additional T_e-dependence for the "experimental" diffusivities. However this should be interpreted as the influence of a parameter, which *could* be the temperature or a related quantity. A causal influence of n_e or T_e cannot be distinguished.

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