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Z-Dependence of Central Particle Transport in ASDEX Upgrade H-Mode Discharges

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Introduction

It has been found on several tokamaks that the radial impurity transport in the confined plasma strongly decreases from the edge to the core. In the core, the transport is temporally discontinuous when sawtooth oscillations are present. In the buildup phase of a sawtooth oscillation the transport coefficients are very low and are greatly enhanced during the crash phase. 'Advanced' discharge scenarios with internal transport barrier (ITB) depend on a profile of the safety factor $q(r)$ which does not allow for sawtooth oscillations. In this paper the core impurity transport of injected impurities with low, medium and high Z number in ASDEX Upgrade H-mode plasmas with and without ITB is assessed.

The general features of core impurity transport in ASDEX Upgrade H-mode plasmas with sawteeth are illustrated in figure 1. In the steady state phase of an H-mode discharge (#10457), argon is puffed for 1s. The density evolution after the start of the puff at t_0=1.95s was evaluated from soft X-ray measurements. It is shown versus the major radius at the mid plane for $\rho_{pol}\leq$0.7. At t=2.05s the argon density in the major part of the plasma is already considerably increased but very little argon has reached the center. Steep radial gradients build up indicating that the diffusion coefficient in the core is very small. This situation persists until the first sawtooth crash occurs. The crash leads to a flattening of the impurity density, i.e. a strong increase of the core transport. After about four crashes a quasi static situation is reached. At this point, the impurity density develops a pronounced peaking in the buildup phase of the sawtooth which is flattened by every crash.

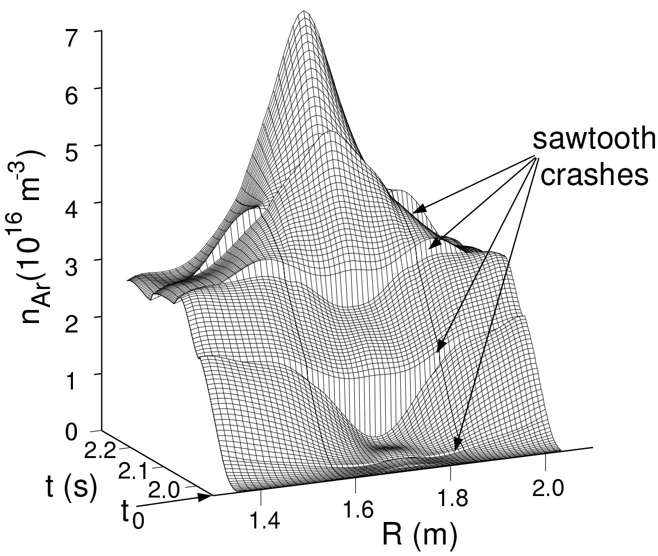

Figure 1: *At time t_0 argon was injected into a steady state phase of an H-mode discharge. The density evolution of argon is shown versus the major radius R in the mid plane. The magnetic axis is at $R_{mag}=1.72$m.*

Core Impurity Transport in H-Mode without ITB

Four different gases (Ne, Ar, Kr, and Xe) were puffed at the mid-plane during the steady-state phase of type-I ELM'y H-mode discharges with neutral beam heating power P_{NI}=5MW, toroidal field B_T=2.5T, plasma current I_p=1MA and safety factor q_{95}=4. The line averaged density was $\bar{n}_e$=7.5$\times10^{19}$m^{-3} which is 60% of the Greenwald limit $\bar{n}_{GW}$. The increase of Z_{eff} due to the puffed impurity decreased strongly with increasing atomic mass and varied between ΔZ_{eff}=0.016 for Xe and 0.3 for Ne.

Three soft X-ray (SXR) cameras with 100μm thick Be-filters (detection efficiency >0.5 for photons in the energy range 2.5-15 keV) served as the main diagnostic tool for this study. Using time averaged data with a time resolution of Δt≈1ms the soft X-ray radiation fluxes from typically 65 line-of-sights were unfolded assuming an emissivity profile $\epsilon_{SXR}(\rho_{pol}, t)$ that is constant on flux surfaces. From the change $\Delta\epsilon_{SXR}(\rho_{pol}, t)$ due to the puffed impurity the time evolution of the impurity density profile $n_I(\rho_{pol}, t)$ was calculated with the total radiative power coefficient L_I^{SXR} in the SXR spectral range, considering the dependence of L_I^{SXR} on radial transport.

The radial transport equation was solved for a time interval from 3ms after the last sawtooth crash to 3ms before the next crash in the radial range $\rho_{pol} < 0.4$. The initial distribution at $t_{crash} + 3\mathrm{ms}$ and the density development at $\rho_{pol} = 0.4$ were chosen as the boundary conditions for the solution. For the diffusion coefficient $D(r)$ a constant value and for the drift parameter $\alpha(r) = v(r)a^2/(2D(r)r)$, a linear function were used. The three coefficients of these test functions were computed by applying a non-linear χ^2–fit to the measured density development for ρ_{pol} <0.4.

Neoclassical transport coefficients were calculated with the numerical code NEOART, which solves the set of linear coupled equations for the parallel velocities in arbitrary toroidally symmetric geometry for all collision regimes. The equations for the banana plateau (BP) contribution are equal to that used by Houlberg [1]. The Pfirsch-Schlüter (PS) contribution is calculated from the coupled equations (6.1-2) and (6.14-15) of Hirshman and Sigmar [2]. For both contributions a reduced charge state formalism is applied. The neoclassical coefficients depend on the ion stage distribution of the impurity which is calculated by the impurity transport code STRAHL. It solves the coupled set of radial transport equations for every ion stage. Toroidal rotation of the plasma is not taken into account and equal temperatures of main ion D and impurity I $T_D = T_I = T$ are assumed.

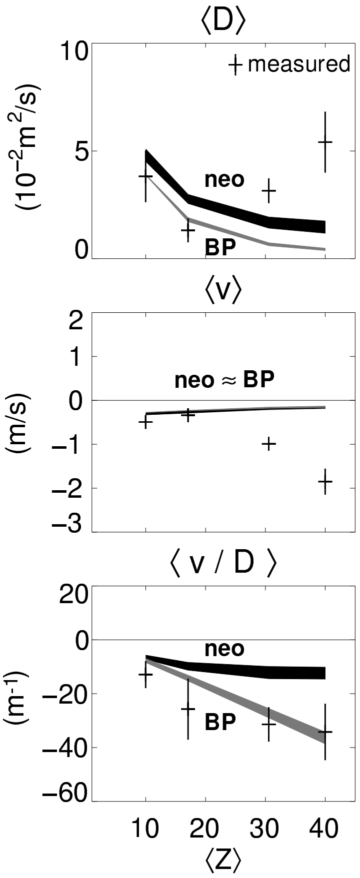

Figure 2: *Line averaged values of measured and neoclassical diffusion coefficient D, drift velocity v and v/D for 0.1<ρ_{pol}<0.3 as a function of the mean atomic charge of the impurity Z in that radial range. The total neoclassical values (label neo) and the BP part are shown as bands representing the cases without C/O concentration and with 1% C and 0.1% O concentration.*

Figure 2 shows the line averaged diffusion coefficient D and drift velocity v for 0.1<ρ_{pol}<0.3 obtained from typically 10 sawtooth cycles versus the line averaged impurity charge Z in the same radial range. The error bars give the standard deviation of the mean value of all analysed sawtooth cycles. Negative values of v represent inward directed drift velocities. With rising Z the convective transport increasingly dominates the diffusive transport which is very small with $D \leq 6 \times 10^{-2}\mathrm{m}^2/\mathrm{s}$. The drift velocity is always directed inward. For Kr and Xe the ratio v/D reaches enormous values of ≈-35m^{-1}. In the simple linear approach with D and v being independent of the impurity density the radial gradient of the impurity profile in equilibrium is determined by this ratio $d\ln(n_I^{eq})/dr = v/D$. However, the linear approach is not applicable when large impurity densities are present which change the deuterium dilution and the temperature profile via additional radiation losses.

The neoclassical values from NEOART are shown as bands representing the cases without inclusion of collisions with C/O and with the 1% C and 0.1% O concentration. D_{neo} is dominated by the BP contribution for low Z and by the PS contribution for high Z. It decreases with rising Z number and is in the same range as the measurements with the exception of Xe. Anomalous diffusion is obviously ineffective in the plasma center. The drift velocity v_{neo} is dominated by the BP value for all Z and is more or less constant. For low to medium Z the measurement is well reflected by v_{neo}, for high Z the deviation is strong. Experimentally, the increase of v/D for high Z is due to an increased inward pinch while the neoclassical calculations have stronger peaking due to a reduced D_{neo}. The ratio v_{neo}/D_{neo} is a factor of 4 too small for high Z.

For Kr a density scan from 45 to 70% of $\bar{n}_{GW}$ has been performed. With rising $\bar{n}_e$ the density profile in the core is flattened while the temperature profile is stiff (constant gradient length). Neoclassical theory predicts a reduced inward directed drift for increasing $\bar{n}_e$ because the inward terms are proportional to the density gradient while the outward terms are proportional to the temperature gradient. The experimental drifts also show a decreasing inward pinch. However, as for the high Z case in figure 2, the calculated drift velocities are a lot smaller than measured.

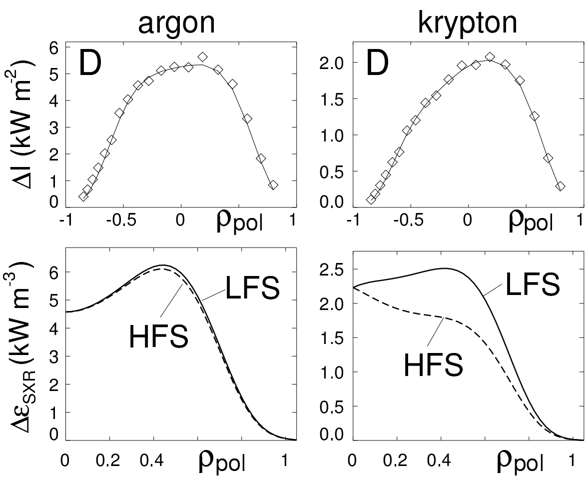

Figure 3: *Unfolding of the SXR-radiation fluxes due to Ar and Kr at Δt=0.2 s after the start of the impurity puff: For Ar the radiation fluxes (◇) can be fitted by a poloidally symmetric emissivity. For Kr the emissivity is peaked on the outboard side. The emissivities are drawn at the mid plane for the low (LFS) and high field side (HFS).*

The strongest deviations of the neoclassical calculations from measurements appear for the heavy elements. A possible explanation might be the toroidal rotation of the plasma which so far is not considered in NEOART. Due to the centrifugal force toroidal rotation causes a poloidal gradient of the impurity density on the flux surface with the maximum density appearing on the outboard side of the tokamak. The effect becomes important for toroidal Mach numbers M_{tor}=$v_{tor}/v_{thermal}$>1. For Ne M_{tor} is ≈0.9 which rises for Xe to M_{tor}≈2.4. Due to the very peaked emissivity profiles that evolve for the high Z elements the detection of inboard/outboard asymmetries is difficult with the camera setup at ASDEX Upgrade and a one dimensional emissivity profile $\epsilon_{SXR}(\rho_{pol})$ represented all measured radiation fluxes with deviations below 5%. Only the early phase after the start of the impurity puff is suited to detect inboard/outboard asymmetries. The impurities are still approaching the center and the profiles of the SXR emissivity are about flat. Fig. 3 shows that for Ar the emissivity is poloidally symmetric while for Kr the emissivity on the outboard side exceeds the inboard value by up to 50%.

Impurity Peaking in H-Mode with ITB

For ASDEX Upgrade discharges with stationary internal transport barrier (ITB) in combination with an H-mode edge [3], no sawtooth oscillations are present and a major concern is the behaviour of impurities in the core. In the core the gradients of T_D and n_D are steeper than in usual H-mode discharges and drive increased neoclassical drifts.

Experimentally, the impurity transport has not yet been investigated in detail, however, first experiments allow to measure the normalized density gradient in equilibrium $d\ln(n_I^{eq})/dr$ which is determined by v/D. In figure 4 results from a stationary ITB discharge with Ar puff are shown. The plasma parameters are depicted in the upper two graphs. Ar was puffed for 1s. For the last 600ms of the puff phase the Ar density for $\rho_{pol}\geq 0.4$ was constant while the central density showed a slow variation. The argon density in this time interval can be treated as quasi static and the according profiles are shown as a band in figure 4.

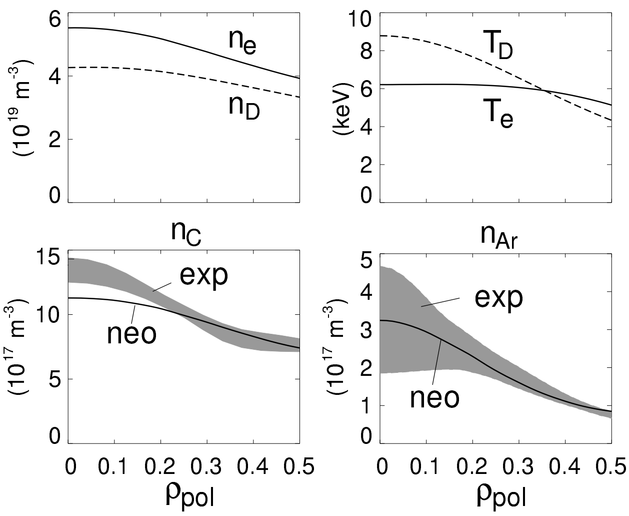

Figure 4: *In discharge #12041 with ITB Ar was puffed for 1s. The plasma parameter during the puff phase are shown in the upper two graphs. Measured equilibrium density profiles of C and Ar are compared with calculated profiles which follow from purely neoclassical transport. The temporarily slowly varying Ar/C core densities are given as bands.*

The equilibrium Ar density profiles that follow from neoclassical transport have been calculated by STRAHL/NEOART where the collisions with carbon which was measured by CXRS were taken into account. No anomalous D and v was used for the radial range which is represented in figure 4. The calculated Ar profile is in accordance with the mean of the measured profiles and thus, v/D is matched by the neoclassical calculation. The measured ratio of central Ar density to the density at ρ_{pol}=0.4 ranges from $n_I^{eq}(0)/n_I^{eq}(0.4)$ =2.2 to 3.3. For C this ratio varies from 1.6 to 1.9 which is slightly above the calculated peaking. In a similar ITB discharge with Kr puff $n_I^{eq}(0)/n_I^{eq}(0.4)$ increased only up to 3-4, which again is very close to the neoclassical calculation. However, due to the high Kr puff level Z_{eff} on axis was $\approx$10 and the the proton density was strongly diluted. In neoclassical theory the plasma dilution leads to a reduction of the inward drift term proportional to the proton density gradient. When the Kr puff is reduced by a factor of 10, the plasma dilution is decreased and calculations with STRAHL/NEOART yield a value of $n_I^{eq}(0)/n_I^{eq}(0.4)$=10 in this case. So far, there is no experimental evidence for this dependence on the Kr puff level. Thus, an increased peaking with increasing Z number is observed. Further experiments with high Z elements are planned to get a better quantification of this increased peaking.

References

HOULBERG, W. A. et al., Phys. Plasmas **4** (1997) 3230.
HIRSHMAN, S. P. and SIGMAR, D. J., Nucl. Fusion **21** (1981) 1079.
WOLF, R. C. et al., this conference.