CENTRAL IMPURITY TRANSPORT IN ASDEX UPGRADE H-MODE DISCHARGES

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1. Introduction

In earlier investigations of the radial impurity transport in the confined plasma of ASDEX Upgrade the diffusion coefficient was found to show a strong decrease towards the plasma center [1]. The central D was measured to be in the range of 0.3–0.6 m^2/s for H-,CDH- and L-mode discharges. These measurements were time averaged and did not distinguish between 'undisturbed' radial diffusion and the additional transport which is caused by sawtooth instabilities. For future 'advanced' discharge scenarios without sawteeth it is important to investigate the effect of these two transport mechanisms separately. In this paper the 'undisturbed' central impurity transport of injected low, medium and high Z impurities in the time interval in between sawtooth crashes is assessed.

2. Experimental Setup

Four different gases (Ne, Ar, Kr, and Xe) were puffed at mid-plane in the flattop phase of type-I ELM'y H-mode discharges with $P_{NI} = 5\mathrm{MW}$, $B_t = 2.5\mathrm{T}$,$I_p = 1\mathrm{MA}$, $q_{95} = 4$ and $n_e \approx 8 \cdot 10^{19}\mathrm{m}^{-3}$. Three soft X-ray cameras with 100μm thick Be-filters (transmission >0.5 for photons in the energy range $2.5 - 15\,\mathrm{keV}$) served as the main diagnostic tool. The electron density was inferred from the DCN interferometer, and electron temperatures were taken from the ECE radiometer data. The puff level was adjusted so that the central plasma parameters were disturbed as little as possible having large enough changes of the soft X-ray signals at the same time. This could be easily achieved for Ar and Kr. To avoid disturbance of the plasma center due to high radiated power densities, for Xe the soft X-ray emissivity ϵ_{SXR} in the center could only be increased by ≈ 0.4 because at $T_e \approx 3000\mathrm{eV}$ the total central emissivity is about a factor of 80 larger than the soft X-ray emissivity. The total radiated power from the plasma bulk P_{rad} changed by about 0.5 MW for all four species. For Ne most of the additional radiation originates from the plasma edge which caused a reduction of ELM frequency by a factor of 2 and an improved confinement leading to a rise of central T_e by 20$\%$ and central n_e of 10%. Fig. 1 shows central n_e and T_e for the discharge $\#10502$ with krypton puff.

Using time averaged data with a time resolution of Δt$\approx$1ms the soft X-ray radiation fluxes from typically 65 line-of-sights were unfolded assuming an emissivity profile that is constant on flux surfaces. This one dimensional emissivity profile $\epsilon_{SXR}(\rho_{pol})$ represented all measured radiation fluxes with deviations below 5%. The central soft X-ray emissivity without impurity puff is modulated by the sawteeth with an amplitude of $\approx 0.3\langle\epsilon_{SXR}(0)\rangle$. For offset reduction the emissivity modulation, which was observed during a time interval $\Delta t = 150\mathrm{ms}$ before the gas injection, was assumed to persist during the puff phase. Thus, the change $\Delta\epsilon_{SXR}$ due to the puffed impurity was obtained by subtracting a time dependent background (see Fig. 1).

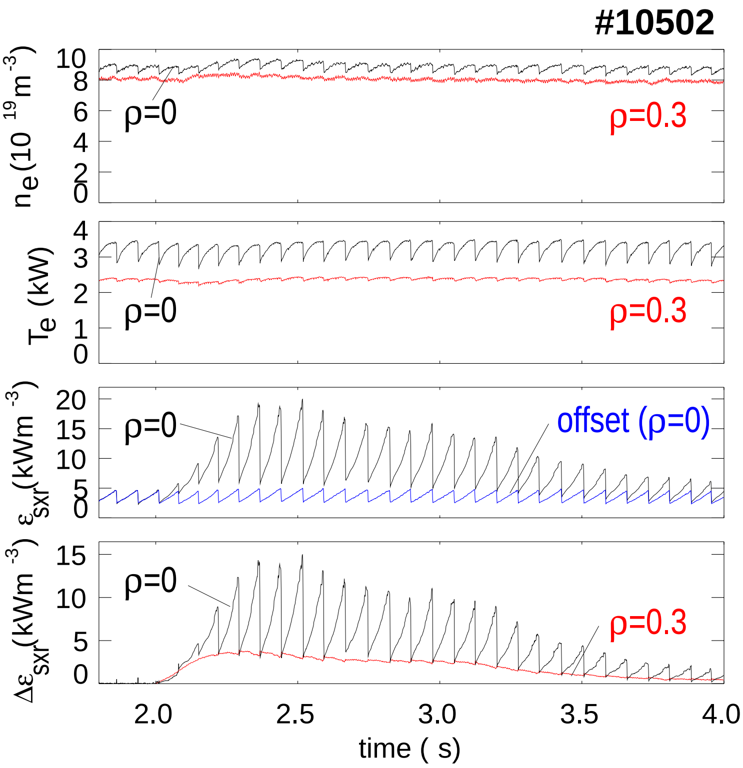

Figure 1. Various time traces for discharge #10502 with krypton injection. For t=1.95-3.0s Kr was puffed at mid plane. The electron density n_e and electron temperature T_e in the center and at ρ_{pol}=0.3 ($q\approx$1) are weakly disturbed. The third time trace gives the central emissivity ϵ_{SXR} in the soft X-ray range and the offset emissivity. Finally, the emissivity change in the soft X-ray range due to the impurity $\Delta\epsilon_{SXR}$ is shown.

3. Radiation Profiles in the Plasma Bulk

One main aspect of impurities in the plasma bulk is the radiation loss. A certain profile of the transport parameters leads to a corresponding equilibrium profile of the impurity density which causes a certain power loss via radiation. For reactor operation radiation profiles with a low center to edge ratio are favorable. Bolometric measurements are dominated by the edge radiation of intrinsic light impurities and the tomographic reconstruction of the total radiation in the plasma center is highly uncertain.

A better approach is to use the soft X-ray profiles which are peaked in the center and can reliably be reconstructed. With the measured electron density and temperature the soft X-ray emissivity profiles of the puffed impurity $\Delta\epsilon_{SXR}(\rho_{pol})$ were transformed into total emissivity profiles $\Delta\epsilon(\rho_{pol})$ for poloidal flux labels ρ_{pol} $\leq$0.5 using the ratio of the respective corona equilibrium radiative power coefficients. Transport calculations with the radial transport code STRAHL [2] confirmed that this corona ratio of the power coefficients approximates the ratio including transport effects to within 10% over the investigated radial range. In Figure 2(a) the volume averaged total emissivity change for $\rho_{pol} < 0.5$ divided by the volume averaged

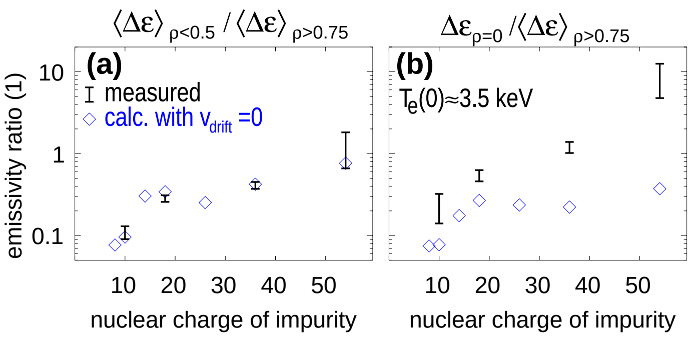

Figure 2. The ratio of time and volume averaged emissivity change due to the injected impurity $\langle\Delta\epsilon\rangle_{\rho_{pol}<0.5}/\langle\Delta\epsilon\rangle_{0.75<\rho_{pol}<1}$ versus nuclear charge Z of the impurity behaves as one expects from transport calculations (◇) with purely diffusive transport (a). However, just before sawtooth crashes the measured emissivity on axis rises more strongly with Z than the calculated value indicating central impurity peaking (b).

emissivity change for $1>\rho_{pol}>0.75$ is shown versus the nuclear charge of the puffed impurity. The change of edge radiation was taken from tomographic reconstruction of bolometry, all values are averaged over sawteeth and were taken in the time interval when the impurity had distributed over the whole plasma bulk. The ρ_{pol} intervals correspond to approximate T_e intervals 100eV–1keV and 2–3.5 keV. The measured emissivity ratios can be found from transport calculations with STRAHL when assuming purely diffusive transport, i. e. for large radial intervals the center/edge ratio of the impurity density is flat. However, when taking the local emissivity on axis just before sawtooth crashes, a much stronger rise with Z compared to the transport results was observed (Fig. 2(b)). Thus, the impurity density peaks in the center and the peaking becomes stronger for elements with higher nuclear charge Z. Note, that for Xe the central emissivity is a factor of 8.6±3.9 larger than the edge value.

4. Central Transport Parameters

Central transport parameters were evaluated by analyzing the temporal evolution of the impurity density profile between sawtooth crashes. With the measured electron density and temperature the emissivity profiles were transformed into total impurity density profiles for poloidal flux labels $\rho_{pol} \leq 0.4$ using the corona equilibrium radiative power coefficient in the soft X-ray range. For the extraction of transport parameters the transport equation was solved for a time interval from 5ms after the last sawtooth crash to 5ms before the next crash in the radial range $\rho_{pol} < 0.4$. The start distribution at $t_{crash}+5\mathrm{ms}$ and the density development at $\rho_{pol} = 0.4$ were the boundary conditions for the solution. For the diffusion coefficient D a quadratic test function $f(r)$ and for the drift parameter $v_{drift}a/2Dr$ a linear test function were used. The 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. An example for the fitting procedure is shown in Fig. 3. The lower graph of Fig. 3 reveals that the sawtooth period is too short for the impurity profile to reach an equilibrium distribution. Thus no information about v/D can be gained from analysis of the static radial density profile.

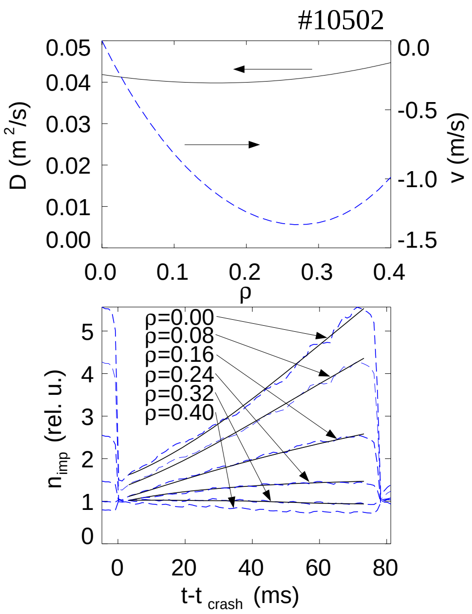

Figure 3. Transport parameters (upper graph) from a χ^2-fit of the density evolution of krypton during one sawtooth cycle. The lower graph compares the measured evolution (dashed lines) with the fit result (solid lines) for various radial positions (ρ_{pol} is poloidal flux label).

Figure 4 shows the line averaged diffusion coefficient $\langle D\rangle$ and drift velocity $\langle v_{drift}\rangle$ for $0.15<\rho_{pol}<0.35$ obtained from typically 10 sawtooth cycles versus the line averaged impurity charge $\langle Z\rangle$ in the same radial range. The error bars give the standard deviation of the mean value of all analyzed sawtooth cycles. Negative values of $\langle v_{drift}\rangle$ represent inward directed drift velocities and positive values outward directed drift velocities. With rising impurity charge $\langle Z\rangle$ the convective transport dominates more and more the diffusive transport and the drift velocity is always directed inward. Since the discharges could not be performed under identical discharge conditions the profiles of electron temperature T_e and density n_e for each of the

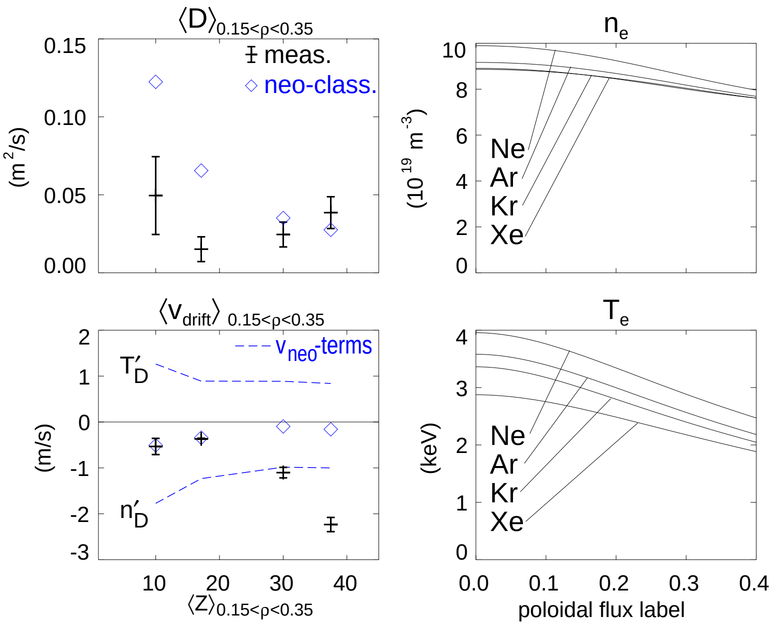

Figure 4. Line averaged diffusion coefficient $\langle D \rangle$ and drift velocity $\langle v_{drift} \rangle$ for the range of poloidal flux labels 0.15$<$ ρ_{pol} $<$0.35 versus impurity charge $\langle Z \rangle$ in the same radial range. The measured transport parameter are compared with results from neo-classical calculations ($\diamond$). The density and temperature profiles for the calculations are shown on the right side.

analyzed discharges are also plotted in Fig. 4 (labeled with the appropriate element). T_e and n_e rise with the amount of light impurities in the discharge (as in the case of a Ne puff). There is no decrease of T_e caused by the small amount of the puffed heavy elements as one can see from the discharge with krypton puff in Fig. 1.

Neo-classical calculations of the transport parameters ($\diamond$ in Fig. 4) were performed assuming $T_D = T_e$ and $n_D = n_e - \sum Zn_Z$. Plasma rotational effects and collisions of puffed impurity and intrinsic impurities were not taken into account. The collisionality ν^* of Xe is about a factor of 5 larger than ν^* of Ne, but all puffed impurities are in the plateau regime in the plasma center. Pfirsch-Schlüter- and banana-plateau-transport was calculated and the sum of the two terms is shown. The diffusion coefficient D_{neo} decreases with rising Z while the drift velocity v_{neo} stays more or less constant (depending on the density and temperature profile). Measured and calculated diffusion coefficients are in the same range and anomalous transport seems to be ineffective in the plasma center. The value of v_{neo} is the sum of an inward directed n'_D-term and an outward directed T'_D-term (dashed lines in Fig. 4) and requires very accurate n_D- and T_D-profiles to be correctly evaluated. However, besides these uncertainties the experimental values show that the increased peaking for higher Z is caused by an increased inward pinch while the neo-classical calculations give a stronger peaking due to a reduction of D_{neo}.

5. Conclusion

A Z-scan of the impurity transport in the plasma center was performed. The diffusion coefficient is compatible with neo-classical values. With rising Z the transport becomes strongly convective with inward directed drift velocities. Very peaked impurity density and emissivity profiles have to be expected in scenarios without or with infrequent sawteeth. The neo-classical drift velocities are not confirmed by the measurements. A comparison with numerically calculated collisional transport will be performed in the near future.

References

[1] S. de Peña Hempel et al.: *Proc. of 24th EPS Conf.* **21A**, 1401 (1997)

[2] K. Behringer: JET-R(87)08, JET Joint Undertaking, Culham (1987)