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Central transport investigations of medium to high Z impurities in ASDEX Upgrade Internal Transport Barrier discharges

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1. Introduction

Much attention is drawn at several tokamaks to discharges with improved core confinement, because of their potential for future tokamak operation. At ASDEX Upgrade discharges with internal transport barrier (ITB) with L mode edges and H mode with improved performance were observed. They are characterized through central ion temperatures up to 15 keV and peaked temperature and density profiles. Under the condition of high core confinement impurity transport studies become especially important, because high Z impurities could cause large radiative power losses in case of accumulation. Especially in regimes without saw teeth, which are typical for ITB discharges, the risk of an impurity accumulation is increased compared to ordinary H mode discharges. The behavior of impurities with medium to high atomic charge numbers (Si, Ar, Fe and Kr) is investigated in ASDEX Upgrade ITB discharges. The transport coefficients D and v are derived using puffs of a small amount of Kr or Ar into the plasma chamber during the plateau phase of the discharge as well as Fe laser ablations [1] causing a measurable increase of the plasma emission. Transport coefficients are obtained by fitting the STRAHL [2] modeled soft X-ray (SXR) emission profiles to the measurements. The trend in Z dependence of impurity transport coefficients is reproduced in an ITB discharge by neoclassical theory. The quantitative comparison of theoretical and experimental transport coefficients will be presented.

2. Experimental method to extract v and D

A separate determination of v and D was done by fast change of the impurity source by using gas puffs in the case of Ar and Kr or by laser ablations of solid targets like Fe or Si evaporated onto a glass substrate. Spontaneous impurity events (Fe, Si) occasionally observed during the discharge were also used for transport investigations. The kind of impurity, which causes an impurity event, was identified spectroscopically using characteristic lines in the emission spectra measured with a Multi Bragg Spectrometer [3] (in the soft X-ray range) and a SPRED spectrometer (in VUV range). During the gas puffs, lasting for approximately 1 s, steady state impurity profiles were established. The gas puffs and the laser ablations were adjusted to cause a clear increase of the SXR signal but not to disturb the background plasma too much. Non stationary impurity profiles following gas puffing, laser ablation or impurity injection, which correspond to net fluxes perpendicular to the magnetical flux surfaces, have been used for evaluation of the drift velocity v and the diffusion coefficient D in this work. For this purpose the additional X-rays produced due to the impurity event were modeled with the impurity transport code STRAHL.

Using measured electron temperature and density profiles, the time development of the impurity density profiles and the corresponding SXR emission profiles for every point of the time grid were calculated under the consideration of an arbitrary anomalous transport parameter set ($v_{anomal}(r)$ and $D_{anomal}(r)$). The modeling also includes the influence of saw teeth (if appear), which flatten the temperature and density profiles in the central plasma and enhance the impurity transport out of the plasma center for a short time.

The absolute SXR emissivities on flux surfaces are obtained by unfolding the line integrals measured along about 50 lines of sight from two soft X-ray cameras. The optimal time resolution Δt is found to be between 1 ms and 5 ms. In this case the raw SXR data are averaged over several time points reducing the fast variation of SXR emission due to ELMs or other plasma instabilities, which would otherwise disturb the further evaluation of transport coefficients. To separate the SXR contribution of the impurities, the background plasma radiation before the impurity event was subtracted. The experimental impurity density for a given radius and time is given by $n_{imp}^{exp} = \epsilon_{imp}^{exp} \cdot n_{imp}^{theo}/\epsilon_{imp}^{theo}$. From the experimental impurity densities the density gradients and fluxes were obtained, which are normalized to the corresponding impurity densities. The linear fit of the normalized fluxes, plotted against the normalized density gradients for different times but for a fixed flux surface, gives the values of v and D on this flux surface [4]: $\frac{\Gamma}{n_I} = -D\frac{\nabla n_I}{n_I} + v$. A negative v denotes an inward drift velocity. Repeating the fit procedure for all available flux surfaces, the radial profiles for v and D are obtained. After the establishment of the equilibrium impurity profiles the linear fit is not valid any more, because the net fluxes perpendicular the magnetic flux surfaces vanish. Therefore only a very short time interval after the impurity injection (typically ≤ 0.3 s) can be used to separate v and D. The $v(r)$ and $D(r)$ are then used in the STRAHL calculation instead of the initial arbitrary values, and the modeling of the impurity transport is repeated iteratively, until the variation of the v and D between the previous and the next iteration becomes below a set threshold, which is of same order as the uncertainty of the method. Actually only 2 or 3 iterations are necessary. The obtained $v(r)$ and $D(r)$ depend on the reliability of the whole input data: T_e, n_e, the atomic data base and especially on the unfolded SXR emission profile. The latter is sometimes strongly influenced by ELMs at the edge making the uncertainty of the measurements large for $\rho_{pol} > 0.8$.

In Fig. 1 experimental transport coefficients for Si, Ar, Fe and Kr for improved H mode discharges are shown. Independent of Z, the transport coefficients for all impurities can be classified as follows: v is negative in the bulk plasma with a minimum between $\rho_{pol} = 0.2$ and 0.4, and large negative values at the plasma edge; the diffusion is maximal at the plasma edge and decreases to small values in the central plasma. At intermediate radii the impurity drift becomes almost zero or even positive, indicating outward drift velocities. Compared to results shown in [5] for H mode discharges for Ar and Kr the drift velocities derived here for ITB discharges with H mode edges at $\rho_{pol} = 0.3$ reach larger negative values (-0.4, -1.0 in H mode and -4.0, -6.0 in ITB correspondingly). The larger v in an improved H mode is also in agreement with the behavior of equilibrium transport coefficients discussed later (see Fig.2) if constant diffusion coefficient are supposed. v and

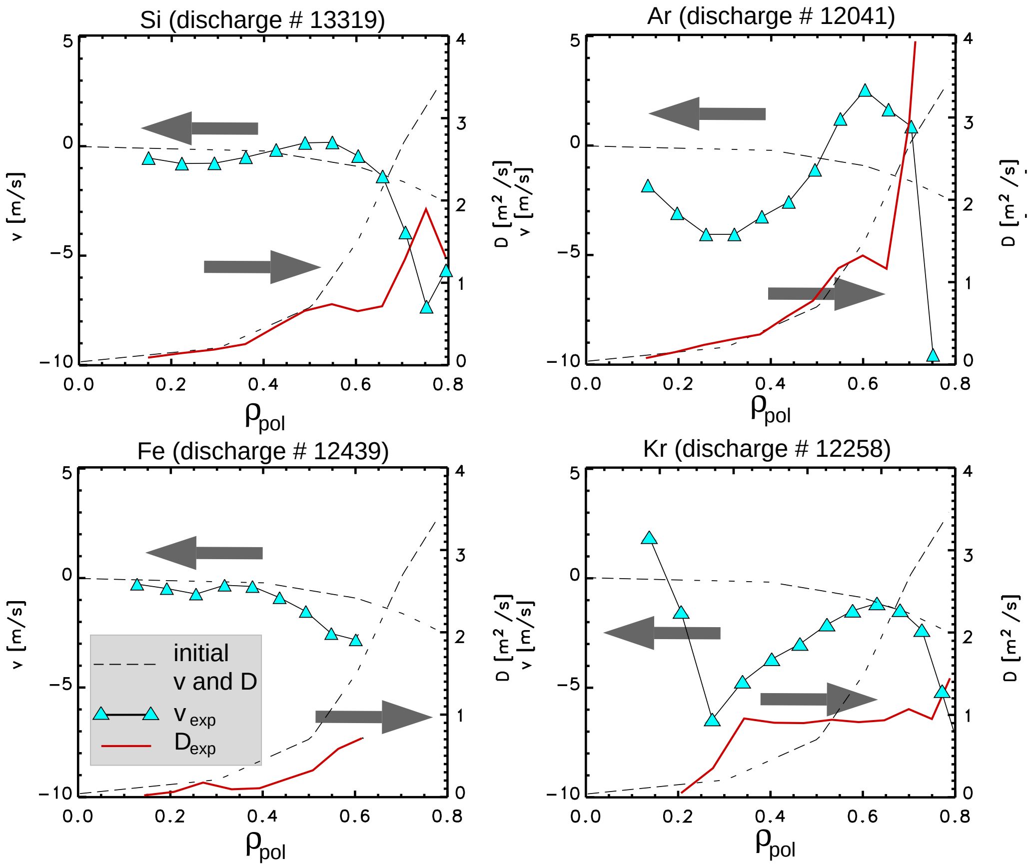

Figure 1. *Transport parameter found for Si, Ar, Fe and Kr in improved H mode discharges. Solid lines show the experimental results: with triangles for drift velocity and without for diffusion coefficient. Dashed lines are the initial parameter of the iteration.*

D calculated with NEOART [6] are typically a factor of 10 smaller (for Si) outside the central plasma region ($\rho_{pol} < 0.2$), compared to the measured ones. In the central plasma, the results of the neoclassical calculations are coincide with experiments in most cases.

3. Neoclassical predictions for stationary transport

After reaching the equilibrium impurity distribution in the plasma column no separate measurement of the diffusion coefficient and drift velocity is possible due to the zero net radial impurity fluxes. The ratio $\frac{v}{D}$ in this case becomes $\frac{\partial ln(n_i)}{\partial \rho_{vol}}$ with the specific flux surface label $\rho_{vol} = \sqrt{\frac{V}{2\pi^2 R_{axis}}}$. It can be evaluated from the experimentally measured impurity density profiles. The velocity density pinch and temperature screening contribute to the drift velocity in the neoclassical approach according to $v_{neo} = D_{neo} Z \left(K \frac{1}{n_i}\frac{\partial n_i}{\partial r} - H \frac{1}{T_i}\frac{\partial T_i}{\partial r} \right)$ with typically $K = 1$ and $H = 0.25 - 0.50$. According to this relation, the tendency of the impurities to form a peaked profile can be inferred. Considering the quasi neutrality of the plasma as well as a constant impurity ion concentration for all flux surfaces, the impurity density differs to the electron density just by a constant factor. For moderate and low impurity concentrations, if no dilution of deuterium (for low Z impurities) or radiative cooling in the plasma center (for high Z impurities) appear, the term $\left(K \frac{1}{n_e}\frac{\partial n_e}{\partial r} - H \frac{1}{T_i}\frac{\partial T_i}{\partial r} \right)$ corresponds to $\frac{v}{DZ}$. Measured electron density and ion temperature profiles together with estimated $\frac{v}{DZ}$ for H=0.25 are shown in Fig. 2. The behavior of the $\frac{v}{DZ}$ in standard high confinement mode discharges is compared with that of discharges with ITB with low and high confinement edges. Experimental electron densities obtained from a DCN

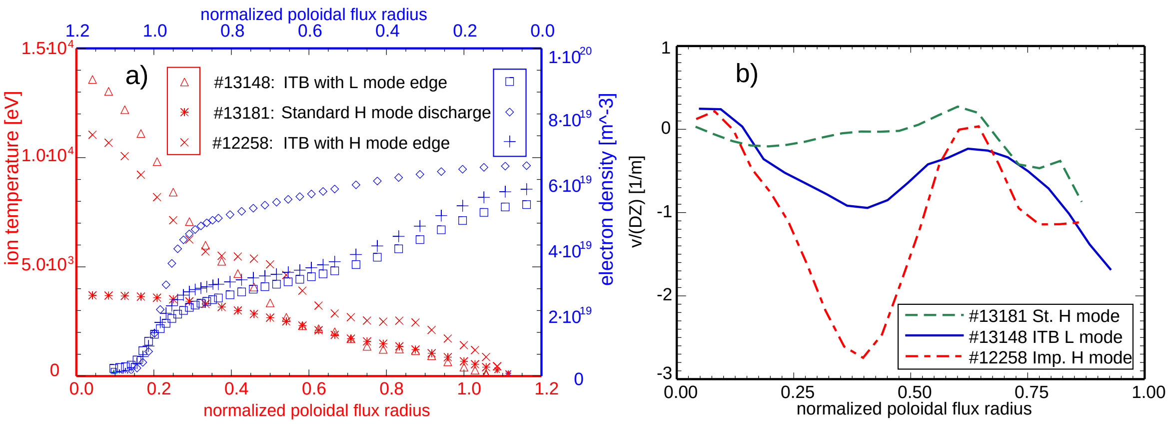

Figure 2. *(a) Electron densities (x-axis inversed) and ion temperature profiles for different kinds of ASDEX Upgrade discharges: ITB with L mode edge, improved and standard H mode; (b) neoclassical $\frac{v}{DZ}$, which correspond to the profiles plotted at (a).*

laser interferometer with channels in the central plasma were combined with a Li beam diagnostic at the edge. Ion temperature profiles from the charge exchange spectroscopy were used. The result is also dependent on a reliable q profile included into the calculations. In all cases plotted in Fig. 2 the same diagnostics as well as the same derivation and smoothing procedures for were used. Therefore a comparison of the results can be done. Negative values indicate a drift velocity in inward direction and more peaked impurity profiles compared to the electron density. The strongest inward drift velocity (if D kept constant) is then predicted for the H mode ITB discharge. $\frac{v}{D}$ values directly obtained from stationary impurity density profiles (Kr, Fe) for improved H mode discharges have a shape similar to that shown above for but those magnitude is about factor of two lower.

4. Conclusions

Negative drift velocities corresponding to inward drift were found in H mode discharges with improved performance at ASDEX Upgrade for spurious amounts of Si, Ar, Fe and Kr. The measured drift is stronger as then the one found in standard H mode discharges [5]. $v(\rho_{pol})$ vanishes for poloidal flux label $\rho_{pol} = 0.45 - 0.60$ for all impurities. Just 10% of the measured drift outside the plasma center could be explained by the neoclassical theory. Hence the anomalous transport should dominate over the neoclassical transport outside the plasma centre under present experimental conditions. ITB discharges with L mode edges should be even more promising from the point of view of impurity transport as one awaits lower inward drifts compared to that of improved H mode.

5. Aknowledgements

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