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On the Dependence of Impurity Transport on Density and Toroidal Magnetic Field in the Stellarator Wendelstein 7-AS

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Introduction - In the W7-AS stellarator the first step global impurity confinement derived from radiation decay times of atoms injected by laser blow-off (LBO) revealed a significant dependence on electron density [1]. Nearly no evidence for a theoretically expected dependence on the toroidal magnetic field strength could be observed on the basis of this evaluation, despite being demonstrated for particle and energy transport. Better assessment of impurity transport was then achieved by more detailed investigation of local transport coefficients derived from analysis of the temporal and spatial evolution of the radiation from the injected aluminium measured by soft X-ray cameras [2]. Compared to low density plasmas, the improved confinement, typically observed at higher densities in ECRH (electron cyclotron resonance frequency heated) plasmas, could be explained by this technique in terms of a general reduction of the local diffusion coefficients [3]. These were found to be quite large in the plasma center and reach small values at the plasma boundary (Fig.1). The latter determines the impurity influx and consequently the time constant for approaching equilibrium density profiles (reaching the order of the discharge time at high density). An increase of Z_{eff} during the pulse duration was found supported by the intrinsic impurity line radiation measurements of the soft X-ray and bolometer cameras as well as X-ray spectroscopy on intrinsic chlorine. This could be shown to be consistent with the derived set of transport coefficients with the assumption of a constant impurity influx from the plasma edge. This assumption is difficult to prove experimentally because flux measurement diagnostics are typically restricted to small spatial areas in the machine.

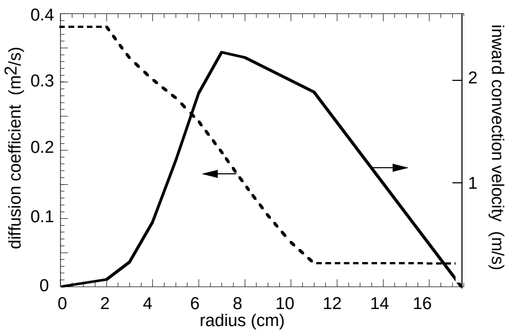
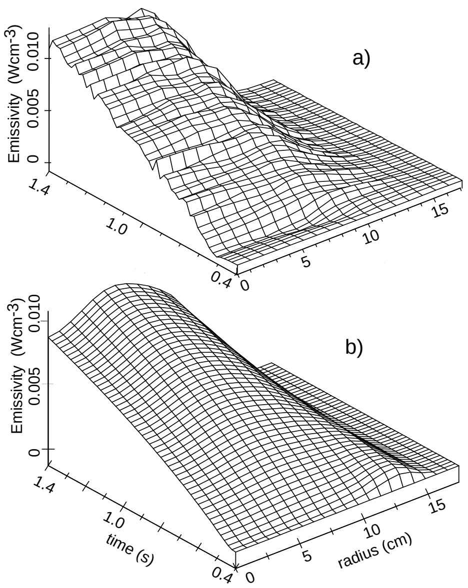


Fig.1: Transport coefficients measured in high density ECRH W7-AS plasma (#36565,$n_e(0)=7x10^{19}m^{-3}$, $T_e(0)$=1.2keV, 2.5T, P(ECF)=400kW)

In order to study exclusively the influence of impurity transport in the presence of constant impurity influx from the vessel wall, perturbing effects of temporally increasing impurity sources (eg. due to thermal load to inboard tiles) have to be avoided. For this purpose, a constant impurity influx is simulated using external gas-puffing of fluorine (CHF_3), having similar recycling properties as the previously observed intrinsic chlorine. Furthermore, the dependence of impurity transport on the toroidal magnetic field strength is studied in more detail by means of local transport analysis of aluminum tracer injection experiments.

Impurity transport in high density ECRH plasmas - The intrinsic impurity radiation does not typically reach a stationary level in high density plasma discharges. This behaviour can only be interpreted in terms of impurity transport, if masking effects such as temporally varying (e.g. increasing) impurity sources are excluded. Up to now, constant impurity influx had been assumed in the simulations. This fitted the experimental data well using simply the transport coefficients derived from impurity injection experiments and without necessity of introducing time dependent intrinsic sources. In order to justify these assumptions, an external gas valve is used to provide a constant fluorine influx (CHF_3, 0.4s-1.5s) into a similar discharge (#46256, $n(0)=7.8x10^{19}m^{-3}$, $T_e(0)$=1.3keV, 2.5T, ι=0.35, P(ECF)=400kW) during the pulse duration. Possible modifications of the effective fluorine source by recycling should be of minor relevance, as being discussed later.

The energy-integrating but radially resolving diagnostics, such as soft X-ray cameras are used to measure the spatial and temporal evolution of the fluorine radiation by taking the difference of shots with and without fluorine puffing. For modelling just the transport coefficient profile (Fig.1) derived in comparable high density ECF-heated discharges is used without any additional modification. As shown in Fig.2 and Fig.3, the relative evolution and the radial profile shape of fluorine radiation measured by soft-X camera is in quite good agreement with the transport code calculations (SITAR [4]). In order to match the absolute intensity, a fluorine influx of $\Gamma=1.4\times10^{13}$ atoms/s cm^2 is chosen in the code calculations. Supplementary calculations with the radiation code IONEQ [5] using the same transport coefficicients reveal that one third of the radiation measured by soft X-ray camera is due to continuum radiation, the radial dependence being quite similar to the measured radiation but not yet implemented in SITAR. For this reason, only the 33% lower level of the contribution of line radiation to the soft-X radiation has to be simulated by SITAR. As a consequence, the influx term in SITAR has to be reduced by the same fraction to approximately 10^{13} atoms/s cm^2. Fig.4 shows the corresponding evolution of the fluorine density as calculated by SITAR, illustrating the large time constant for achieving stationary impurity density profiles due to low diffusion coefficients at the plasma boundary. The predicted radial evolution of the fluorine density (at t=0.405s/0.6s/1.4s) is normalized to and compared with the electron density profile in Fig.5. A



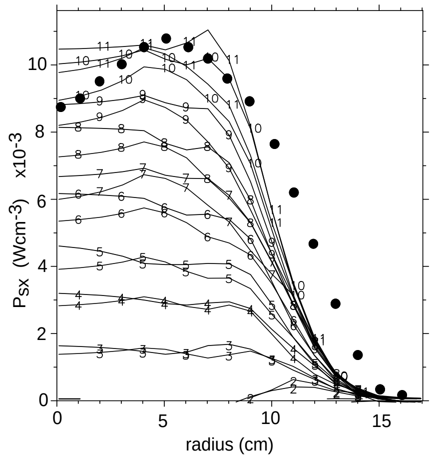


Fig.3: Temporal evolution of radiation profiles as measured by soft X-ray cameras (same as in Fig.2: solid lines, #1:o.4s up to #11:1.4s in steps of 0.1s) compared to the calculated one (SITAR) at 1.4s (solid dots).

Left: Fig.2: a) Temporal evolution of Abel-inverted fluorine radiation profiles measured by soft X-ray camera behind 5 microns Be-filter compared with b) evolution predicted by SITAR. Gas-puff starts at 0.4s

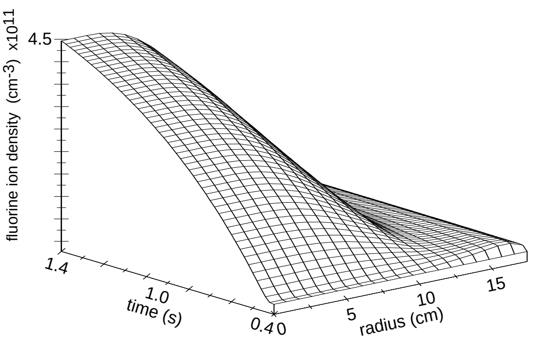


Fig.4: Calculated (SITAR) evolution of fluorine density in a high density ECRH discharge (#46256) with constant external fluorine gas puffing.

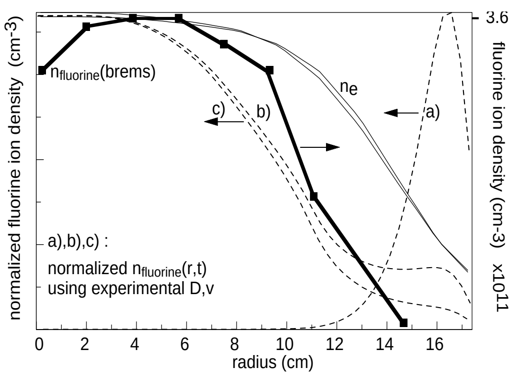


Fig.5: Calculated evolution (SITAR) of radial fluorine density distribution (at t= a) 0.405s, b) 0.6s, c) 1.4s, dotted lines) normalized to and compared with electron density profile, and the fluorine density profile at t=1.3s derived from bremsstrahlung (solid squares, solid line).

clear peaking of the fluorine density profile with respect to the electron density profile in the radial region of large ratio of v/D (r > 8cm, see Fig.1) is indicated. This result could be supported by the additional independent method as described below.

Calculation of the radial distributions of the different ionization states of fluorine with the IONEQ code, using the derived transport coefficients and the actual plasma parameters, reveals that the total density of fluorine ions is quite close to the density of fully stripped fluorine atoms (F^{9+}) over a broad radial range (Fig.6): $n_{F,tot}(r) \approx n_{F9+}(r)$. This condition offers the possibility to reconstruct the radial distribution of total fluorine ions from the radial bremsstrahlung profiles as routinely measured by the Z_{eff}-diagnostic (using a spectral region around 1030nm which is found to be free from line radiation). The result is presented in Fig.5 for t=1.3s and shows a quite good agreement with the predicted profile at t=1.4s based on the measured transport coefficients. The absolute values for the central fluorine density at t=1.3s - being 3.6×10^{11} cm^{-3} (from bremsstrahlung, see Fig.5) and 4.3×10^{11} cm^{-3} (prediction resulting from derived transport coefficients, see Fig.4) - agree within 20%. This is a quite satisfactory result with respect to the completely different approaches. Comparing these values with electron density, a central fluorine concentraton of 0.5% is reached at t=1.3s.

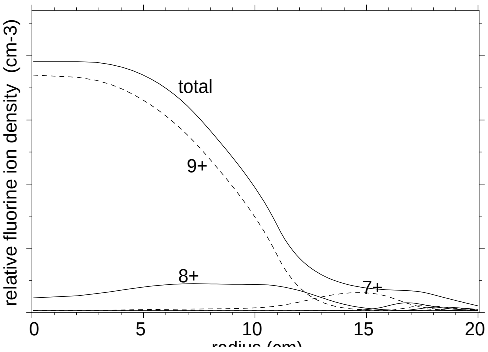


Fig.6: Radial distribution of ionization states of fluorine in the high density discharge #46256 under investigation.

In the presence of recycling, the constantly applied gas puff might be superimposed by recycling fluxes from the vessel wall which can develop proportional to the fluorine concentration in the plasma and violate the aspired condition of a constant impurity source. Due to the few discharges with relatively low amount of injected fluorine the vessel wall is not saturated by fluorine. Although the recycling flux is difficult to assess, a maximum contribution corresponding to 25-30% of the external source is estimated. Here, a maximum achieved fluorine density of nearly 4×10^{11} cm^{-3}, an impurity confinement time in the order of 1s (decay time to 1/e-value as observed in this type of discharge) and a recycling coefficient of R=1 (which is indeed much less for non-noble gases like fluorine) is used. More realistic recycling coefficients will lead to even smaller recycling fluxes which should not severely modify the applied external source.

Dependence of impurity transport on toroidal magnetic field - The scaling law derived for the radiation decay times in LBO experiments [1] indicates only a weak dependence of the impurity confinement on the toroidal magnetic field ($\propto B^{0.3}$). From neoclassical theory a strong dependence of the impurity diffusion coefficient D ($\propto 1/B^2$) is predicted, but also in the case of anomalous transport some dependence on B would be expected. The measured decay times are global quantities being sensitive to both, D and v, which additionally might vary strongly across the plasma. Therefore, the comparison of local transport coefficients in discharges with different toroidal magnetic field is required, in particular the diffusion coefficient because it is independent of gradients in density and temperature profiles.

Since the ECRH power deposition depends strongly on the magnitude of the magnetic field, NBI (neutral beam injection) heated plasmas have been investigated at B=1.25T and 2.5T. However, the electron temperature and density profiles deviate significantly, although same line-integrated electron density, rotational transform ι=0.35 and heating power P_{NBI}=500kW was chosen, as shown in Fig.7. This difference of the profiles reflects to a large extent the improved energy confinement at 2.5T. Calculations using FAFNER code [6] reveal comparable radial profiles of total NBI-heating power density within only 10-15%. Slightly higher values at B=2.5T in the central part of the plasma are due to 40-50% better coupling to the ions compared to 1.25T. Additionally, the onset of some mode activity is observed in the high field case causing perturbations of the local transport analysis. Nevertheless, there exist certain time intervals, in which the mode activity is sufficiently reduced so that local transport coefficients could be derived. As presented in Fig.8, the diffusion coefficient in the central part of the plasma is in fact clearly reduced in the high field case, as theoretically expected. Obviously, there is no evidence of reduced confinement (increased diffusion coefficient) due to the presence of modes in the high field case in the present experiments. An interesting feature is, that the radiation decay times are nearly identical, while there are differences in the rise of impurity radiation after injection of aluminum by LBO which are mainly due to the different existing diffusion coefficients in both cases. This indicates a higher contribution of inward convection to the radial transport in the case of small magnetic field (B=1.25T), compensating the faster decay caused by larger diffusion coefficients as measured for this case. It is not quite clear whether this behaviour might also be a basis for the explanation of the general insensitivity to B in the scaling law for the decay times.

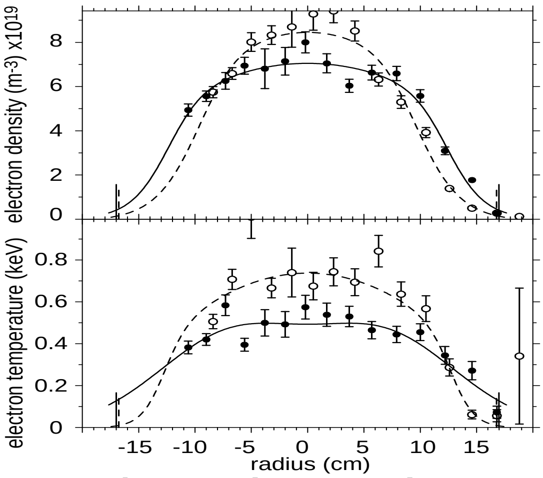


Fig.7: Electron density and temperature profiles measured in NBI-heated discharges at different toroidal magnetic field B=1.25T (#48075 solid line) and B=2.5T (#4826 dashed line) both at the same line-integrated density

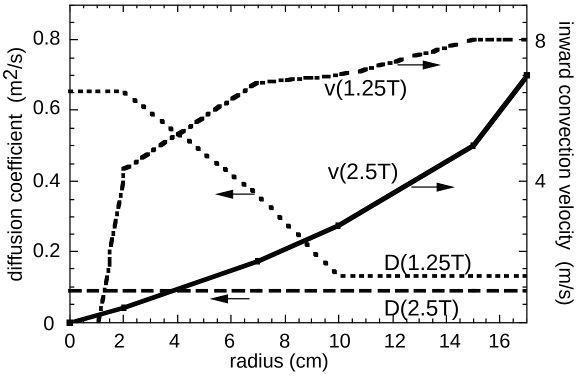


Fig.8: Comparison of experimentally derived impurity transport coefficients for NBI-heated plasma discharges with toroidal magnetic field B=1.25T (#48075) and 2.5T(#48165)

Summary - The slow increase of impurity radiation and Z_{eff} typically observed during the pulse duration in high density ECRH plasmas is investigated using two different experimental approaches: (a) predicton of the impurity density evolution by a transport code using the radial profile of transport coefficients measured by LBO, and (b) calculation of the impurity density profiles from bremsstrahlung. Effects such as temporally varying impurity sources cannot completely be excluded to contribute to the observed behaviour. Therefore, experiments with constant fluorine gas-puffing are performed in order to elucidate the impurity behaviour only in terms of transport. The observed fluorine density evolution agrees well with the predicted ones (using the measured transport coefficients) and is consistent with the fluorine density profiles derived from bremsstrahlung. Both methods reveal good agreement in profile shape, and absolute fluorine density within 20%. Furthermore, a peaking of the total fluorine density profile with respect to the electron density profile has been identified in the outer half of the plasma where large values of v/D exist. The experiment demonstrates that the observed impurity behaviour at high density can be characterized by the measured transport coefficients without necessity to consider time dependent impurity sources for the simulation. Certainly, there might exist other scenarios, where non-stationary sources have to be considered additionally.

Moreover, experiments at B=1.25T and 2.5T indicate a decrease of impurity diffusion coefficient at higher toroidal magnetic field strength.

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