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Comparative study of intrinsic edge impurities in the W7-AS stellarator during high confinement discharges

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After installation of the island-divertor at W7-AS /1/, a new improved confinement regime for the plasma energy could be established with central electron densities up to $n_e(0)=4 \times 10^{20} m^{-3}$. Full density control and quasi-stationarity characterize this regime. Experiments with Al as an injected impurity have shown that above a certain threshold density of $\langle n_e \rangle=1.5\text{-}2 \times 10^{20} m^{-3}$, the impurity confinement time drops from values of several hundred milliseconds down to a few ten milliseconds. Simulation of these laser blow-off experiments (LBO) indicate a reduction of the inwards velocity during the transition while the diffusion coefficient remains approximately constant /2/. However these derived transport coefficients are restricted to the plasma core and do not necessarily reflect transport of intrinsic impurities at the plasma edge. In the present study, the behaviour of intrinsic carbon impurities in the plasma edge region is studied.

Impurity transport analysis

Radial profiles of C^{6+} in the edge region were obtained from charge-exchange (CX) spectroscopy using a high energy Li-beam /3/.The distribution of C^{6+} is simulated by a simple 1D-transport model and compared to the experimental data. The equations of continuity and radial particle flux for the z-th ionization stage of carbon are:

$$\frac{\partial n_z}{\partial t} = -\frac{1}{r}\frac{\partial}{\partial r}(r\Gamma_z) + Q_z \qquad \Gamma_z = -D\frac{\partial n_z}{\partial r} + v n_z$$

with the density n(r,t) and a term Q including sources and sinks in effective radial coordinates r. The radial particle flux Γ(r,t) is represented by a diffusive and convective part. This set of coupled equations are solved for the distribution of charge states $n_z(r,t)$ with the IONEQ code /4/ using input data of measured n_e, T_e and T_i profiles. The code models the ionization and recombination process and the radial transport. The radial location for the carbon source is specified at an effective radius a=15 cm which is the approximate position of the graphite divertor targets. The $n_z(r)$ profile depends mainly on the ratio of v/D, not on the individual values of D and v. For D a radial constant value, determined by the LBO experiments, was used. For v, a linear profile v=v(a)r/a was assumed. These assumptions are identical to the transport analysis of the LBO experiments. IONEQ runs with different values of v(a) were carried out. By comparisons with the experimentally measured C^{6+} profiles, the ratio of v(a)/D and the central carbon concentration is determined which fits the data best. Signals were time-averaged in flattop-phases and the simulation time was set to the middle of the time interval.

Discharges with high ion temperatures

Shown in Fig.2 are the results when this analysis is applied to discharges with optimized confinement and high ion temperatures where plasma profiles (Fig.1) are well documented and the Li-beam covers a large radial region /5/. A value of D=0.1 m^2/s was used. Data fit best for an inward convection of v(a)=-3 m/s. The absolute value of v(a)/D=30 m^{-1} agrees well with the LBO results. This strong inward convection is consistent with the observation that bolometer radiation and bremsstrahlung rise slowly during the discharge. The impurity profile is centrally peaked (Fig.3). The central concentration $n_{C6+}/n_e(0)$ of the simulation is as high as 5%. The physical origin of the inward convection is conjectured to be the strong negative radial electric field /5/. The resulting poloidal rotation of highly charged impurities causes a frictional force, which in connection with the toroidal magnetic field drives the impurities inwards.

Fig.1) Plasma profiles of discharges with high ion temperatures. YAG=Thomson-scattering, ECE= electron cyclotron emission, NPA=neutral particle analyzer.

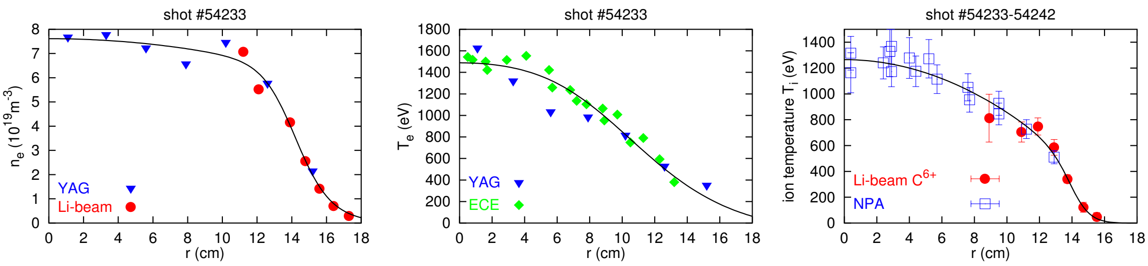


Fig.2) High ion temperatures: IONEQ calculations with convection velocity v(a) as parameter and data from Li-beam CX.

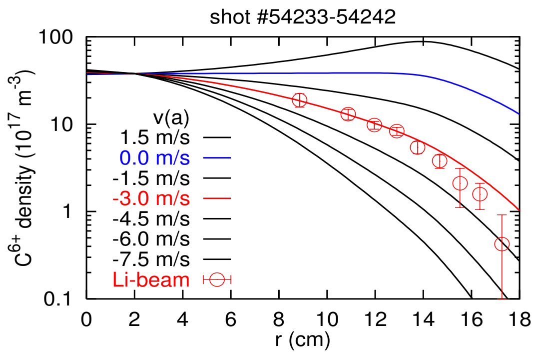
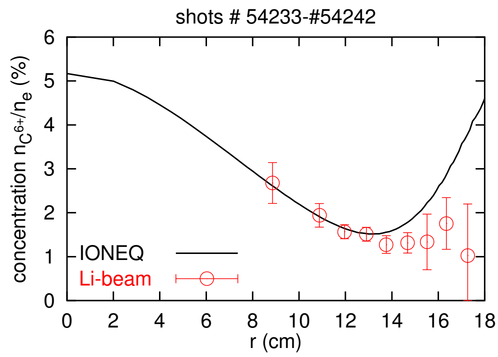


Fig.3) High ion temperatures: C^{6+} concentration from IONEQ calculations and measured data from Li-beam CX.



Transition from normal confinement (NC) to high-density-H-mode (HDH)

Discharges with 1 MW NBI within an island divertor configuration were carried out in the vicinity of the threshold density to the HDH-mode /6/. Fig.4 shows the corresponding plasma profiles. Unfortunately, there is only vacuum magnetic field line tracing available at present for the mapping to effective coordinates. Finite beta effects ($\beta(0)\approx1\%$) may explain large discrepancies of radial positions between different diagnostics. To account for these effects, the Li-beam coordinates were shifted to r-1cm and the ruby Thomson scattering to r+1cm. $T_i=T_e$ was assumed due to lack of diagnostic data. The kinetic energy from the profile fits (NC: 7.0 kJ, HDH:12.6 kJ) is in good agreement with the measured diamagnetic energy. The same value of D=0.115 m^2/s was used for both NC and HDH, which is consistent with the LBO analysis. Fig.5 shows the results for NC. A best fit to the data is found using v(a)=-8.5 m/s and $n_{C6+}/n_e(0)=0.6\%$ (Fig.7). Fig.6 shows the results for HDH. A best fit to the data is found using v(a)=-1.7 m/s and $n_{C6+}/n_e(0)=0.3\%$ (Fig.7).

These results are in general agreement with the results from the LBO transport analysis of comparable discharges at r<10 cm /2/. The inwards velocities at the plasma edge are slightly higher than the linear extrapolation of the LBO values (NC: v(a)=-6 m/s, HDH: v(a)=0 m/s). The very low C^{6+} densities at r>13 cm suggest that in this region v/D is higher. Nevertheless, since the calculated distribution of C^{6+} is very sensitive to T_e below 200 eV, an overestimation of T_e in this region would have a similar effect.

It might be argued that there is ambiguity in the analysis since both $n_{C6+}(0)$ and v(a) are treated as free parameters and agreement might be found for different sets of parameters. However, v(a) determines the slope of the curves and a variation of $n_{C6+}(0)$ results only in a vertical shift of the profile on the logarithmic scale. For this reason, v(a) is varied to fit the slope of the experimental data and $n_{C6+}(0)$ is matched to their absolute values. In HDH, fits of the experimental data with a similar strong inward v(a) as in NC fail, as indicated by the different slopes. Furthermore, such a fit would result in very high central carbon concentrations which is in contradiction to the low impurity radiation from the plasma center.

The results rather support a drastic reduction of the inwards velocity during the transition to the HDH-mode, also for intrinsic impurities near the plasma edge. The smaller convective term is consistent with both: the observations that intrinsic impurities do not accumulate during HDH and that the fact that density control as well as stationarity is maintained. The much smaller central carbon concentration $n_{C6+}(0)$ in HDH results in a lower central Z_{eff}. The $n_{C6+}/n_e(r)$ profiles in NC and HDH are qualitatively in accordance with results from bolometry, which show that during the transition to HDH the radiation zone moves from the plasma centre to the edge /7/.

The physical origin of the favourable impurity transport in HDH and the vast change of the plasma profiles is not clear at present. The role of the radial electric field is an issue of current research.

Fig.4) Electron density and temperature profiles for normal confinement (NC, empty symbols) and high-density H-Mode (HDH, filled symbols), Ruby= edge thomson scattering system, Li=Li-beam.

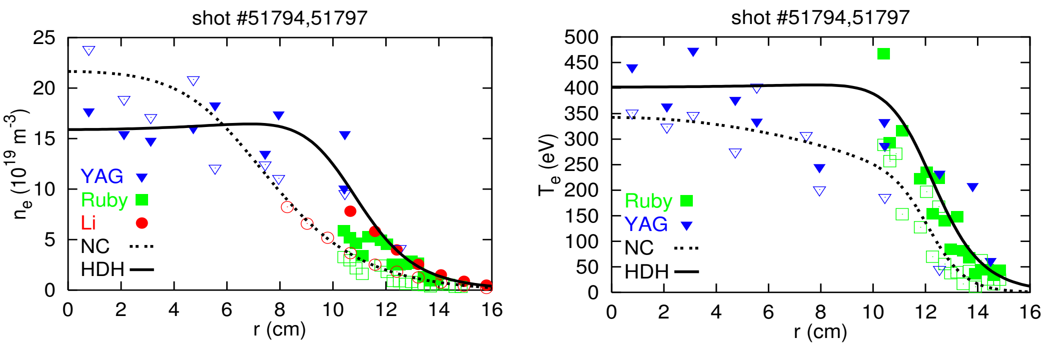


Fig.5) Normal confinement: IONEQ calculations with v(a) as parameter and measured data from Li-beam CX.

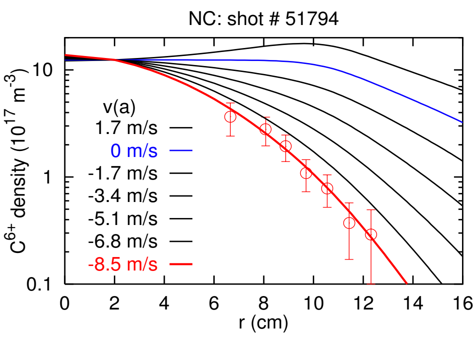


Fig.6) HDH-mode: IONEQ calculations with v(a) as parameter and measured data from Li-beam CX.

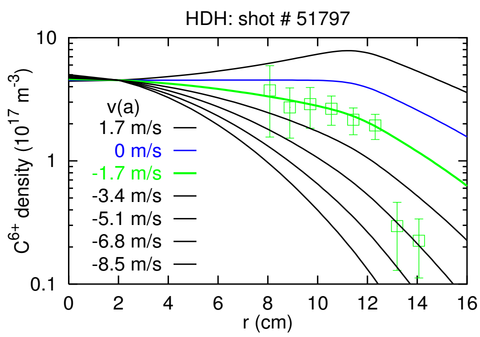
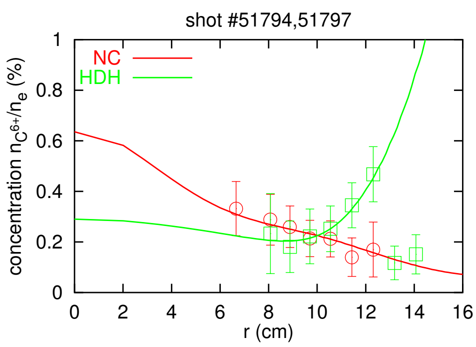


Fig.7) Normal confinement and HDH-mode: C^{6+} concentration from IONEQ and measured data from Li-beam CX.



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