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Characterization of impurity transport in the W7-AS stellarator during the transition to the improved confinement regime

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Introduction - The impurity confinement in ECF-heated W7-AS plasmas with a limiter configuration revealed a strong and unfavourable dependence on density ($\tau_I \approx n_e(0)^{1.2} x P_{ECRH}^{-0.8}$) /1/. Stationary radiation levels could usually be sustained at low and medium density. Towards higher densities (> 5 x $10^{19}m^{-3}$) the impurity confinement successively increased due to a reduction of the diffusion coefficient. This caused a rise in impurity radiation throughout the pulse duration, being predicted to saturate at times longer than the pulse length /2/. Densities higher than the cut-off frequency of the ECR heating systems (1.2 x 10^{20} m^{-3}) could be achieved only in NBI heated plasmas. They show a similar high impurity confinement as well (e.g. low impurity diffusion coefficients D(r)=0.05-0.07 m^2/s and large inwards convection v(r)=(5m/s)(r/a) at central densities around $10^{20}m^{-3}$), often suffering from a loss of density control and a degradation of plasma energy by radiation losses. The installation of island divertor modules in W7-AS /4/ finally provided access to a new improved confinement regime (High Density H-mode, HDH /6/), which allows NBI heated operation at central electron densities up to 4 x $10^{20}m^{-3}$ under quasi-stationary and controlled conditions. Using hydrogen as working gas, the transition from usual behaviour (Normal Confinement NC) into the HDH-regime is characterized by a certain threshold density above which the electron density profiles suddenly flatten and a reduction of the impurity confinement in conjunction with a simultaneous improvement of energy confinement is observed.

Transition from NC to HDH – Fig.1 shows the variation of the impurity confinement time with density in a series of flat-top NBI-heated (1MW/2MW) discharges in a standard magnetic divertor configuration /3/. The corresponding impurity transport was studied by the laser blow-off technique (LBO) using aluminium as tracer material. The impurity confinement time was derived from the decay time of line radiation from the highest existing ionization state of aluminium (Al XII, 0.776 nm) which is centrally peaked at the relatively low temperatures in both regimes (appr. 300-500eV centrally) (Fig.4). Beyond a certain power dependent threshold density (1.5-2 x $10^{20}m^{-3}$) the usual unfavourable density scaling of impurity confinement changes drastically and the confinement time drops from values of several hundred milliseconds down to values comparable to the energy confinement time (few ten ms) within a small density interval . The total radiation which is typically peaked in NC becomes flat. Simultaneously, the electron density profile flattens dramatically with steep edge gradients, accompanied by an increase of plasma energy and an energy confinement time, exceeding the values predicted by the W7-AS- and International Stellarator Scaling (ISS95) (Fig.1). The profile change can nicely

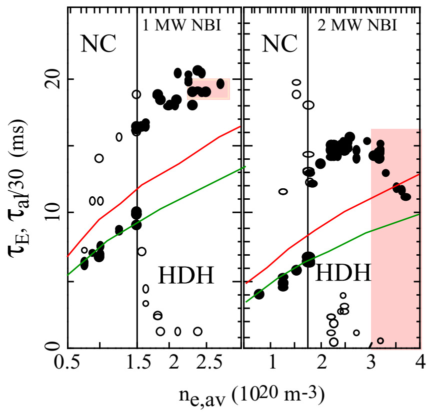

Fig 1: Energy- (black dots) and aluminium (open circles) confinement times vs. electron density at 2 NBI powers; green line: ISS95-scaling, red line: W7-AS-scaling.

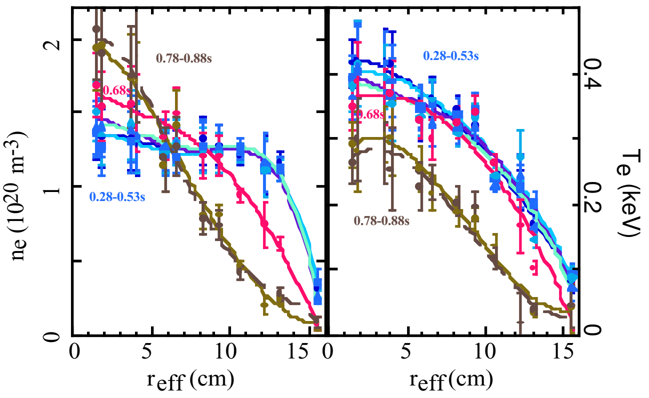

Fig.2: Change of electron density and temperature profiles during the transition from NC(brown lines) to HDH (blue lines) in a 1MW NBI-heated plasma at threshold density (#55595)

be demonstrated in a 1MW discharge close to the density threshold where the transition occurs within the pulse duration (Fig.2). The lowest impurity confinement times were observed when the plasma partially detached at highest densities (Fig.1: red shaded areas, Fig.3). The different impurity confinement times in both regimes are correlated to a generally different temporal evolution of the intrinsic impurity species (Fig.3): the long decay times in NC indicate a good impurity confinement and cause a steady increase of impurity radiation throughout the pulse duration; the short confinement times in HDH point to a degraded confinement allowing NBI heated operation at central electron densities up to 4 x 10^{20} m^{-3} without radiative collapse. The transition, however, was also observed in non-standard divertor configurations with smooth separatrix.

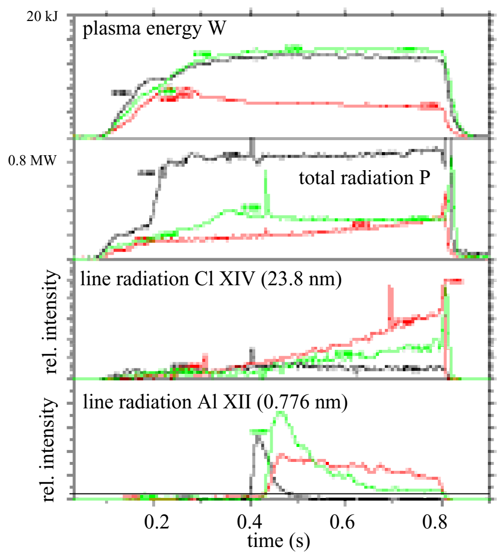

Fig.3: Behaviour of energy, total radiation, intrinsic Cl-radiation and aluminium radiation following LBO injection for NC (red,#51882), HDH (green,51889) and detached plasma (black, #51051) in 2MW NBI discharges

Impurity transport analysis – In order to roughly elucidate which key quantity is changing during the transition to HDH, the evolution of Soft-X camera radiation seen with a 25 micron beryllium filter and the spectral emission from Al X-XII ions (Al X (55nm), Al XI (33.3nm), Al XII (0.776nm)) following aluminium LBO (Fig.4) was simulated (SITAR code) using just a simple transport model (D(r)=constant v(r)=(r/a)v(a), minor radius a). The simulations indicate a significantly reduced inwards velocity v(a) (2MW: from 10m/s to 2.5m/s; 1MW: from 6m/s to no inward velocity) at the transition to HDH while the diffusion coefficient D (around 0.07-0.12 m^2/s) remains nearly unchanged. This is also supported by intrinsic carbon density profiles obtained from CX measurements using a Li-beam /5/. Aiming to predict the behaviour of intrinsic impurity species in these two transport scenarios, the derived 2 sets of transport coefficients were applied to a constant aluminium influx (representative for intrinsic species)

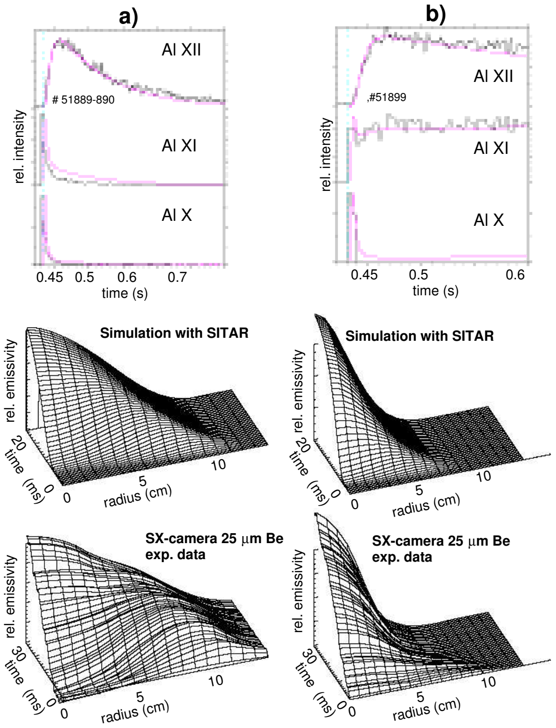

Fig.4: Simulation of Al line emission (top) and background-subtracted Soft-X camera evolution (bottom) after LBO, using a simple transport model (D(r)=const., v(r)=(r/a)v(a), injection time set to t=0s for SITAR) for a) HDH, b) NC with 2MW NBI

throughout the discharge. The totally different behaviour of the calculated central aluminium density is shown in Fig.5 for the 2MW NBI case: In NC, the high inward velocity causes the aluminium ion profiles to peak and to approach stationarity on a very long time scale outside the pulse length. Within the discharge time only accumulation of the aluminium ions (to quite large central concentrations compared to HDH) can be observed. The reduced inwards velocity in HDH leads to smaller time constants for achieving stationary impurity profiles. Consequently, quasi-stationarity is achieved well within the pulse length. These results are qualitatively in good agreement with the experimental observations in Fig.3. In order to provide some physical picture for the experimental observations, the radial electric field E_r is suggested to be the origin for the driving mechanism of the

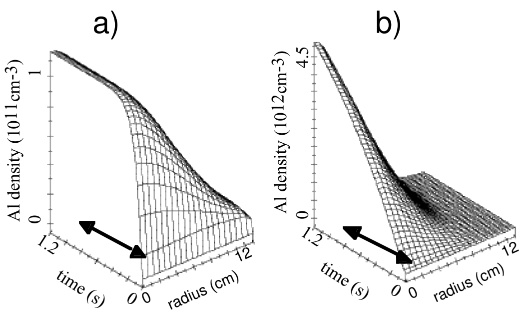

Fig. 5: Predicted evolutions of aluminium density (representing an intrinsic species) using the derived D,v and for constant Al influx (arbitrary value$10^{13}cm^{-3}s^{-1}$, but same for both regimes) for a) HDH and b) NC regime for 2MW NBI (see Fig.4)

inward pinch v. In a simplified model, proportionality between the convection velocity and the radial electric field $v(r)(m/s)= C_m \times Z \times E_r(r)/T_i(r)$ (V/m) (C_m: proportionality factor, Z: impurity ionic charge) was assumed. $E_r(r)$ was taken from the pressure gradients in the radial force balance equation $E_r \approx (1/n_e) x (dP_e/dr)$, taking $T_e=T_i$ at these high densities and neglecting any plasma rotation for simplicity. The radial profiles of D(r) were adjusted in order to match the experimental time traces. Both regimes could be simulated well (MIST code) using the same proportionality factor and radial profiles for D. The resulting transport coefficients are shown in Fig.6. They confirm principally the same trend as already indicated using the simple transport model, but now in more detail: during the transition to HDH the inward velocity is remarkably reduced over a wide radial range in the core plasma, but can be strongly increased at the plasma edge . The small peripheral region of large diffusion compensates the accumulating effect of the convection "barrier" at the plasma edge by diffusion fluxes, so that the plasma reveals a reduced impurity confinement. The validity of the assumptions has still to be proofed experimentally (e.g. by E_r-measurements in well diagnosed plasmas), in particular at the plasma edge, where confinement relevant mechanisms might be complex and rotation can become relevant /5/.

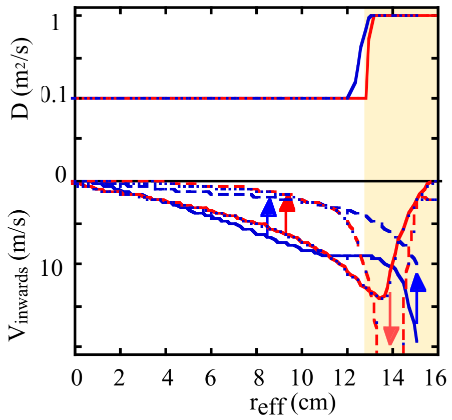

Fig.6:Transport coefficients D(r), v(r) for a 1MW NBI (red) and 2MW NBI (blue) plasma in the NC (solid lines, #55587/51881) and HDH (dotted lines, #55540/51889) regime.

Summary– The installation of divertor modules in W7-AS provides access to a new improved confinement (HDH) regime for NBI-heated plasmas beyond a certain power dependent threshold density (1.5-2 x $10^{20}m^{-3}$), exhibiting high energy- and low impurity confinement. As a result, NBI heated operation at central electron densities up to 4 x $10^{20}m^{-3}$ under quasi-stationary and controlled conditions without radiative collapse became possible. The sudden degradation of the impurity confinement after the transition into HDH could be attributed to a reduction of the inwards velocity, wheras the diffusion remains nearly unchanged. Different radial electric fields in NC and HDH are discussed as a possible driving mechanism for the convection velocity.

References

[1] R.Burhenn et al.,Proc. 1995 22nd EPS Conf. on Contr. Fusion. and Plasma Physics (Bournemouth) **19C** Part III, 145 (1995)

[2] R.Burhenn et al. ,Proc. 1997 24nd EPS Conf. on Contr. Fusion. and Plasma Physics (Berchtesgaden) **21A** Part IV, 1609 (1997)

[3] P.Grigull and al., Plasma Phys. Controlled Fusion, **43**, A175 (2001)

[4] H.Ehmler et al., this conference

[5] Yu. Igitkhanov et al., this conference

[6] K. McCormic et al., in print: Phys. Rev. Lett. Vol.89