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Island Divertor Experiments on the W7-AS Stellarator

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1. Abstract

In the past, under limiter conditions, it has been impossible to produce high-power, high-density, quasi-stationary neutral beam injection (NBI) discharges in W7-AS. Such discharges tended to evince impurity accumulation, lack of density control and subsequent radiation collapse (Normal Confinement). Presently, W7-AS is operating with a modular, open island divertor similar to that foreseen for W7-X. The divertor enables access to a new NBI heated, high density ($\bar{n}_e$ up to 4×10^{20}m^{-3}) operating regime (High Density H-mode). It is extant above a threshold density, and is characterized by flat density profiles, high energy- and low impurity confinement times and edge-localized radiation. The HDH-mode shows strong similarity to ELM-free H-mode scenarios previously observed in W7-AS, but in contrast to these avoids impurity accumulation. These new features enable full density control and quasi steady-state operation over many confinement times (at present only technically limited by the availability of NBI) also under conditions of partial detachment from the divertor targets.

In HDH-mode, even in attached discharges, the divertor target load is considerable reduced. This is mainly due to favourable upstream conditions (higher n_{es}), edge localized radiation and increased power deposition width. The benefits of the HDH-mode do not restrict only to hydrogen plasmas. They also occur – albeit in a modified manner – in deuterium plasmas. Undoubtedly, there are clear isotope effects between hydrogen and deuterium discharges.

The results obtained in W7-AS render good prospects for W7-X and support the island divertor concept as a serious candidate for devices with magnetic islands at the edge.

2. Results

Fig. 1 summarizes the behaviour of the energy confinement time $\tau_E = W/P_{abs}$, the normalized radiated power P_{rad}/P_{abs}, and separatrix density n_{es} obtained from quasi-stationary discharges with P_{abs}=1.4 MW as a function of the line-averaged density $\bar{n}_e$. τ_E-values in NC follow the scaling $\tau_E^{ISS95}=0.26\times \iota_a^{0.4}\times B_t^{0.83}\times a^{2.21}\times R^{0.65}\times \bar{n}_e^{0.51}\times P_{abs}^{-0.59}$, [2], whereas for the HDH-mode one finds $\tau_E \sim 2\times \tau_E^{ISS95}$. P_{rad}/P_{abs} grows smoothly with $\bar{n}_e$ until partial plasma detachment, where a jump in the normalized radiated power occurs. The separatrix density n_{es} increases sharply at the NC → HDH-mode transition point, then continues to climb with $\bar{n}_e$ and saturates before dropping at partial detachment. Fig. 2 juxtaposes n_e-, T_e- and pressure-profiles, $P_e(r)$, for NC and HDH-mode discharges, P_{abs}~1.4 MW. In deuterium the n_e-profiles seem to be somewhat broader than in hydrogen, whereas the T_e- and P_e-profiles essentially retain their shape. Attendant to HDH-mode is a dramatic flattening of the n_e-profile with a sharp gradient at the edge, whereas $T_e(r)$ and $P_e(r)$ taper. The NC→HDH-mode transition is accompanied by a change in stored energy from W~8 to ~20 kJ owing to profile changes as well as higher peak values of n_e. Fig. 3 shows radiation profiles $P_{rad}(r)$ measured by a bolometer array. NC is afflicted by peaked $P_{rad}(r)$, whose magnitude increases in time. In HDH-mode they remain stationary with time, and are concentrated at the plasma edge. As Fig. 3 shows, this is more pronounced in deuterium than in hydrogen discharges, [4].

In the case of hydrogen plasmas, a study of the spatiotemporal behavior of highly ionized states of laser-ablated aluminum shows that the impurity diffusion coefficient in NC and HDH-Mode does not change significantly, whereas the inwards drift in HDH-Mode decreases by a factor of ~4, [3]. During the HDH-mode the reduced inwards pinch evidently causes diffusion to dominate over convection, leading to a reduction of impurity peaking.

The H_α-view of the lower divertor target plate during the HDH-mode is shown in Fig. 4. Obviously, the strike zone at the right hand side of target plate #12 – which is closest to the plasma boundary – splitts up, and thus increasing the power deposition width. The splitting up in HDH-mode is also demonstrated by I_s- and T_e-profiles measured at position #13 with flush-mounted Langmuir probes, see Fig. 5b. Fig. 5a shows the analogous profiles at position #5. In both positions the electron temperature in HDH-mode is reduced significantly compared to NC discharges. This is due to higher n_{es} and edge localized radiation in the HDH-mode.

The maximum power density on target plates in discharges with P_{abs}=1.4 MW and various densities is shown in Fig. 6. In island divertor configurations this usually falls on plate #3, which is more distant to the plasma boundary, but has a high incident angle of the magnetic field lines (~20°). Also shown is the peak power density at target plate #12, where the plasma detaches at high densities. At the onset of detachment a sharp drop of the power density to ~0.2 MW/m^2 is observed in this case. At plate #3 the plasma always remains attached. In HDH-mode the power density falls continuously with density until ~0.5 MW/m^2 for hydrogen and ~1 MW/m^2 for deuterium, respectively.

The power deposition width λ_q of the strike zone in the region #5 and #13 for different densities $\bar{n}_e$ and P_{abs}=1.4 MW is shown in Fig. 7. $\lambda_q = \int_{peak} j_s(r)T_e(r)dr/(j_sT_e)_{\max}$, with $j_s(r)$ and $T_e(r)$ measured by Langmuir probes. In NC regime λ_q generally decreases with density. In HDH-mode λ_q increases by a factor of two at position #13, mainly, due to the splitting up of the strike zone. In hydrogen plasmas, at position #5, λ_q does not change significantly from its moderate value in NC. However, in deuterium plasmas a favourable isotope effect is observed, i.e. a considerable increase of λ_q even at position #5, which may be a consequence of an enhanced edge transport in deuterium discharges.

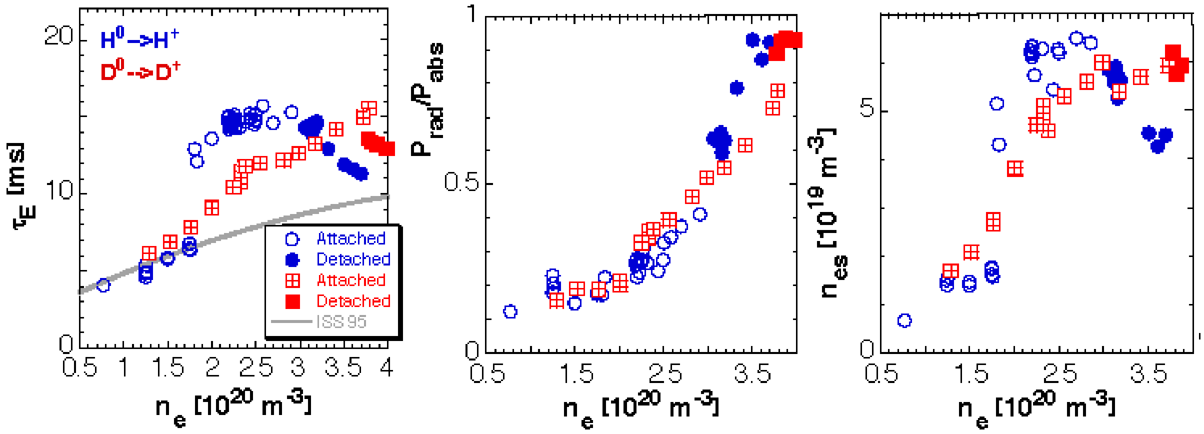


Figure 1: Comparison between hydrogen and deuterium discharge series: energy confinement time τ_E, radiated power fraction P_{rad}/P_{abs}, and separatrix density n_{es}, [1]

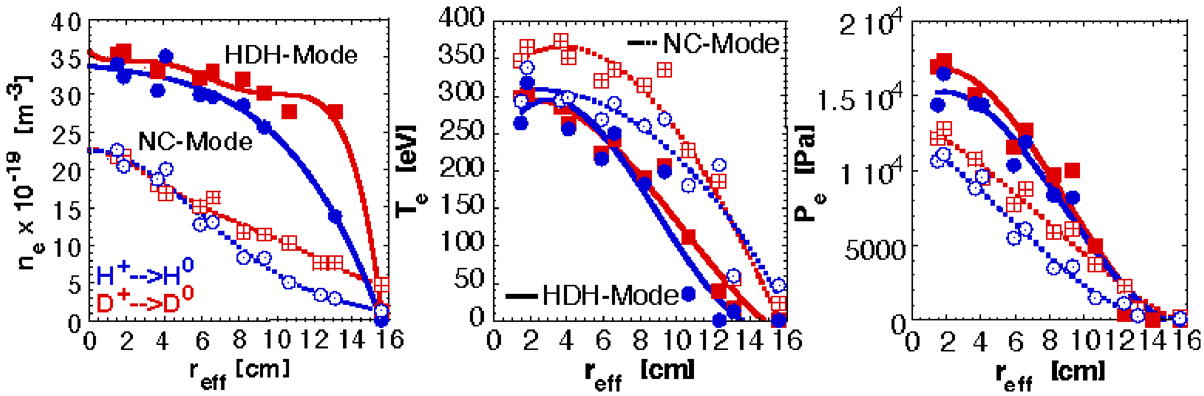
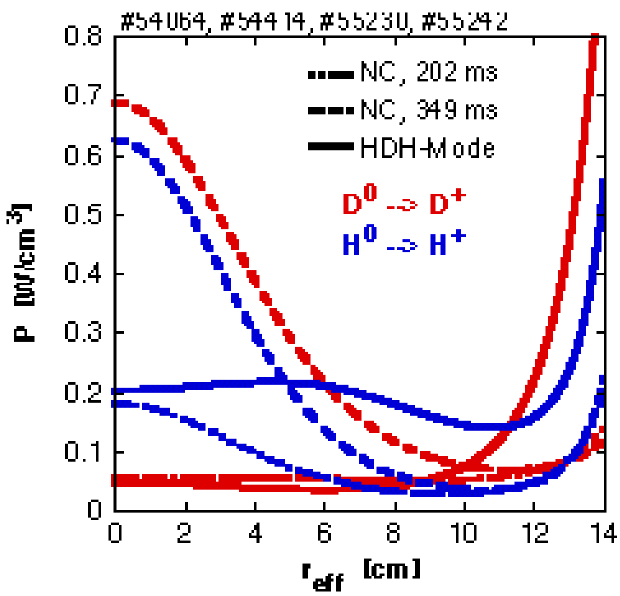


Figure 2: n_e- T_e- and pressure profiles, $P_e(r)$, in hydrogen and deuterium plasmas, in NC and HDH-mode discharges, B_t=2.5T, [1]



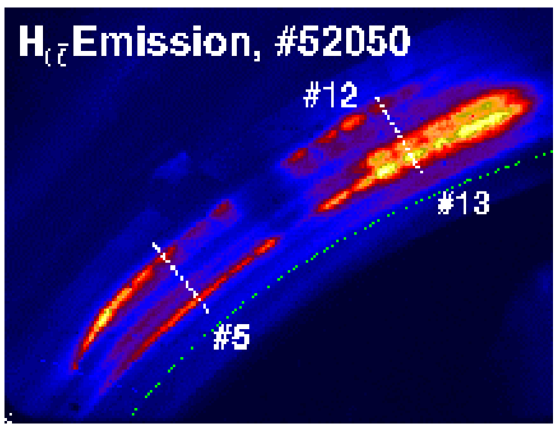


Fig. 3: Radiation profiles from bolometry *Fig. 4: H_{α}-light of the bottom divertor module*

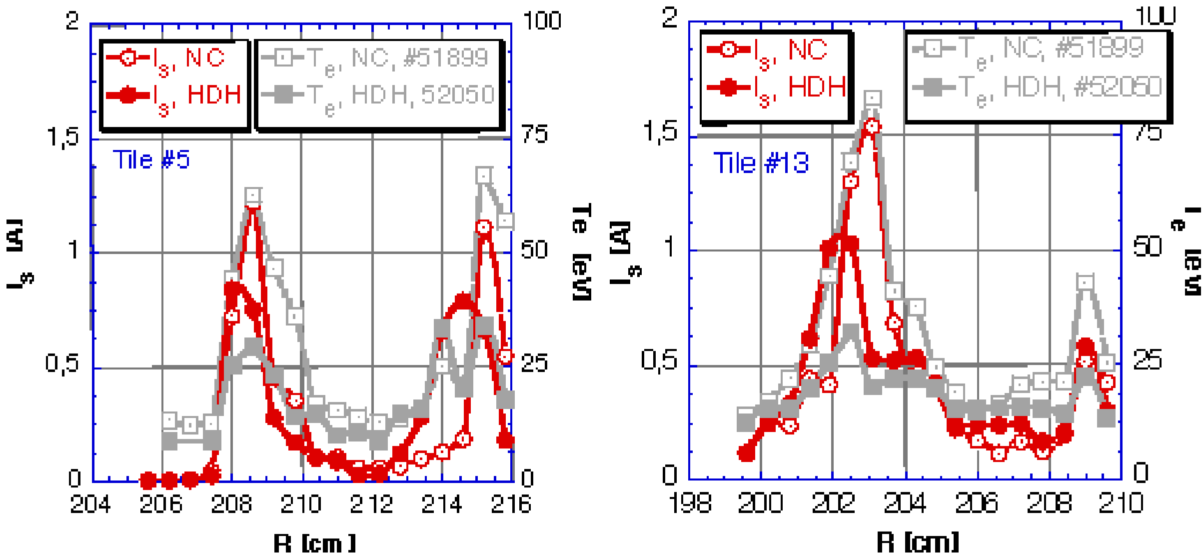


Figure 5: I_s- and T_e-profiles measured by Langmuir probe arrays in position #5 and #13

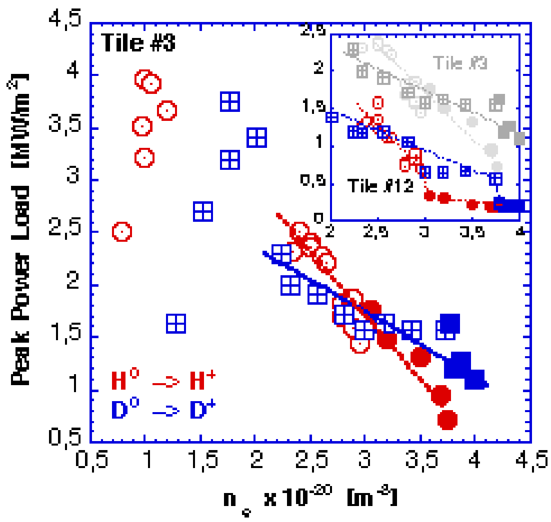


Figure 6: Power density to target plate #3 (i.e. the peak power load on the divertor module) and plate #12 (i.e. the closest point to the plasma) for a n_e-scan, measured by IR thermography, P_{abs}=1.4MW. Full symbols denote partially-detached conditions.

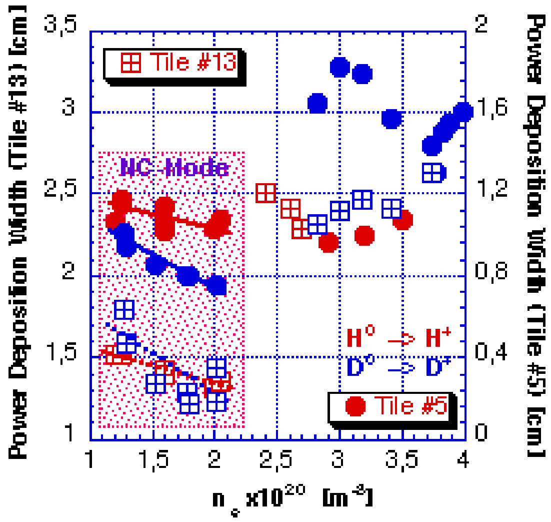


Figure 7: Power deposition width of the strike zones at position #5 and #13 determined from $j_s T_e$-profiles, measured by Langmuir probes, in hydrogen and deuterium discharges

3. References

[1] K.McCormick et al., to be published in J. Nucl. Mater.

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[4] L.Giannone et al., this conference, 2002