

The Wendelstein W7-AS High Density H-Mode A Mode for the Future?

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Introduction: The High Density H-Mode (HDH) /1-3/, discovered and exploited over a wide range of conditions on the W7-AS stellarator, combines optimal core behavior along with edge parameters necessary for successful operation of an Island Divertor. Potentially this bodes well for the larger W7-X device ($a/R = 0.16/2\text{m}$ vs. $0.5/5.5\text{m}$) which represents the next step in the Wendelstein line of development. Still, the question remains if the HDH properties of high energy confinement with low impurity retention and radiation localized at the edge under steady-state conditions (ELM-free) at high densities (to $4 \cdot 10^{20}\text{m}^{-3}$) and heating powers (to 1.7MWm^{-3}) can be realized on W7-X or other stellarators?

Early investigations revealed that the differences in energy confinement between normal confinement- (NC) and HDH-modes were related to the much broader density profiles of HDH, in contrast to the peaked profiles of NC /1/. Further, the diminished residence time of laser-ablated aluminum in HDH compared to NC could be modeled in an ad hoc fashion by a smaller inwards impurity pinch in the core plasma /1, 4/. Neoclassical calculations indicated that temperature screening together with the flat n_e -profiles could be the physical factors for this reduced pinch. However, the inwards convection associated with steep density gradients at the plasma edge for HDH would nonetheless still contrive to confine impurities within the core plasma. A postulation of enhanced impurity diffusion at the plasma edge was necessary in order to reproduce the impurity flushing features of HDH /5, 6/.

It is of note that the Enhanced D α H-mode (EDA) of the C-Mod tokamak has properties similar to HDH, e.g. flat n_e -profiles and steady-state, ELM-free operation without impurity accumulation. A quasi-coherent (QC) mode at the plasma edge is thought to provoke impurity flushing /7-9/. In contrast, ELM-free H-modes without QC exhibit accumulation.

This paper reports on dedicated experiments performed on W7-AS to compare HDH with standard ELM-free discharges (H^*) – which typically suffer radiation collapse as a result of impurity accumulation. A back-to-back comparison offers an excellent basis for pinpointing essential operative elements of HDH physics.

Experiment: A discharge was tailored in an island-divertor configuration with $P_{\text{abs}} \sim 1.4\text{MW}$ whereby the density was ramped up until attainment of H^* , and then after 60ms increased again until the HDH mode was solidly established (Fig.1). The entrance into H^* is indicated by the cessation of ELM activity (seen in H_α of Figs. 1&2), followed by a rapid increase in

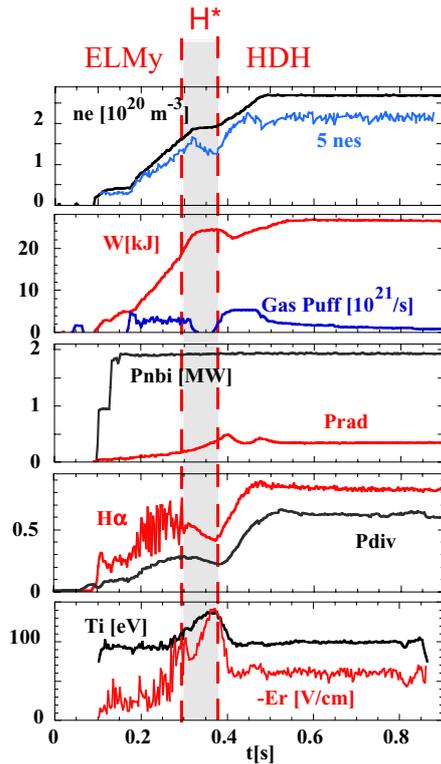


Fig.1: line-averaged density n_e , density at separatrix n_{es} , stored energy W , H_α from divertor, subdivertor neutral pressure P_{div} , ion temp. T_i & E_r along a BIV chord in density gradient region. ELMy, H^* & HDH phases are indicated.

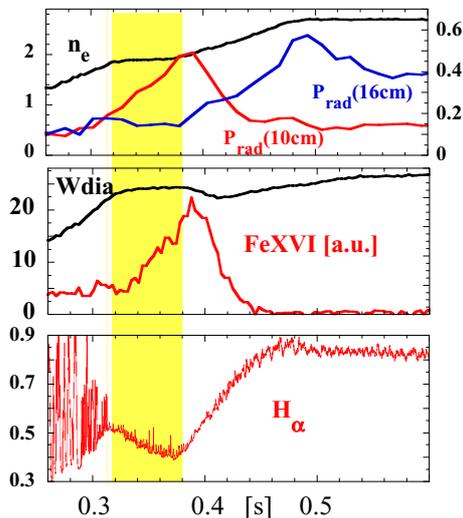


Fig.2: Expanded time scale from Fig.1: Radiation along bolometer chords P_{rad} , FeXVI line intensity from core. H^* -phase is indicated.

global radiation P_{rad} as registered by a bolometer array. A constant density plateau during H^* was enabled by He glow-discharge cleaning before each series discharge in order to promote pumping by the graphite divertor target plates. Otherwise, n_e normally rises during H^* . The maximum length of the H^* plateau was dictated by the goal of a good transition to HDH within the same discharge. Were the 2nd n_e -ramp delayed by another 10ms then radiation collapse would no longer be avoidable. For the scenario developed here, the n_e -ramp stops the runaway of P_{rad} (P_{rad} of Fig. 1 & FeXVI of Fig. 2). Simultaneously, the radiation moves outwards, shown by the temporal evolution of bolometer chords at 2/3 radius and the plasma edge (10 & 16cm traces of Fig. 2). The P_{rad} profiles (Fig.3)

illustrate that the initially flat distribution at the start of H^* (0.315s) quickly changes to a hollow profile whose amplitude increases with time. In contrast, the transition to HDH is accompanied by a dramatic peaking of $P_{rad}(r)$ outside the confinement region, with little change in the global radiation level.

The density increase needed to provoke the H^* HDH transition leads to a marginal augmentation of plasma energy, but the decay times for laser-ablated aluminum are radically different: no falloff of AlXII radiation is observed over the H^* -phase, whereas for HDH the e-folding time constant is the order of 100ms /6/. The n_e - and T_e -profiles for H^* and HDH (Fig. 4) are evidently of the same form, so a change in impurity transport based largely on n_e -profile shapes – as for NC and HDH – cannot find application. The collisionality ν^* for HDH is more than a factor of two higher (Fig. 4). Nonetheless, in both cases C^{6+} is collisional and H^+

is collisionless over most of the radius: These are necessary conditions for temperature screening to play a role, leading to an outwards-directed impurity flux.

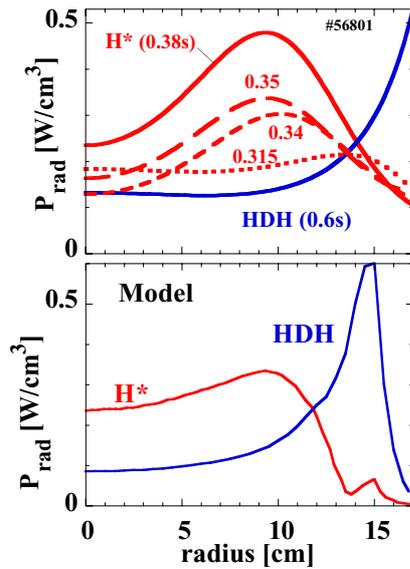


Fig. 3: Experimental and modeled P_{rad} profiles.

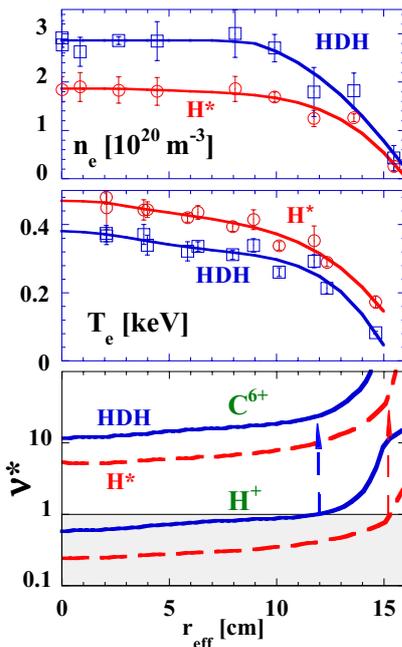


Fig. 4: n_e - & T_e -profiles for shot of Figs.1-2. v^* profiles.

The temporal behavior of ablated aluminum as well as the qualitative form of the $P_{\text{rad}}(r)$ profiles can be described by assuming no difference in transport between H^* and HDH in the core plasma, and enhanced impurity diffusion for HDH in the steep gradient region. The effect is to drive impurities to the vicinity of the H-mode edge transport barrier in both cases. For H^* , without enhanced diffusion in the gradient region, impurities then accumulate with a hollow radiation profile, whereas for HDH they are flushed further to the outside. Fig. 3 illustrates the qualitative behavior of $P_{\text{rad}}(r)$ for such model conditions, juxtaposed against $P_{\text{rad}}(r)$ from experiment. Within these

considerations no statements are possible concerning background ion transport. The fact that the radial E_r -field

(Fig.1), as measured by a passive BIV viewing system, is higher in H^* may indicate steeper pressure profiles – but without the actual n_e - and T_e -profiles at the edge (undergoing evaluation) this remains a speculation.

Discussion and Summary: Since an unidentified mechanism is postulated to expel impurities from the edge region in HDH and not in H^* , the discharge scenario under discussion should enable one to more easily discriminate against phenomena not of principle importance for HDH. Mirnov coils mounted on the wall as well as on a fast-scannable probe have been used to register the electromagnetic spectrum in all discharge phases. In contrast to C-Mod where the QC mode is detectable by Mirnov coils only very near the plasma surface (due to the high poloidal number /8/), on W7-AS there is: a) no difference in spectrum between wall-mounted coils and those very near the plasma, b) no

strikingly obvious difference in H^* and HDH phases, and c) no consistent presence of any particular mode for a variety of HDH discharges – even though it is not uncommon to see weak coherent oscillations in the 80kHz range. The plasma edge has also been probed for density fluctuations using a microwave reflectometer. A dedicated k-scan over $k_\theta \sim 0$ -10cm⁻¹ for a frequency range 5-250kHz did not detect any mode activity. The cutoff density of $\sim 6 \cdot 10^{19} \text{ m}^{-3}$ placed the reflecting layer in the density gradient region just inside the separatrix. Measurements at other frequencies, corresponding to cutoff densities of ~ 8 and $12 \cdot 10^{19} \text{ m}^{-3}$

yielded similar results. An H_{α} channel viewing the midplane plasma found low-level, low-frequency spectra (<10kHz) in HDH and not H^* , whereas the global H_{α} signal from the divertor plate saw no differences. A target plate Langmuir probe sampling an island divertor flux tube from the outer circumference saw spectra similar to the midplane H_{α} channel while other probes sensitive to inner flux tubes saw no differences between H^* and HDH. All-in-all, the picture concerning HDH-related fluctuations of any nature is not conclusive. More detailed evaluation of experimental material is required. It is already reasonably evident, however, that a QC mode as on C-Mod is not part of the story.

In any case, high collisionality seems a factor: HDH has never been found for low-collisionality plasmas. Indeed, a minimum threshold density exists which increases with power /1/. But collisionality is perhaps only one element – as exemplified by the H^* -HDH comparison. Possibly the neutral pressure plays a direct role: The sub-divertor neutral pressure increases more than a factor two during the transition from H^* to HDH (Fig. 1) as does the main chamber pressure (not shown, but attaining $\sim 10^{-4}$ mbar). Interestingly, an important aspect for an EDA-like mode on the JFT-2M tokamak is thought to be saturated wall conditions leading to high wall recycling and very high neutral pressures – thereby motivating the name “High Recycling Steady H-Mode” /10/.

The HDH mode can exist in a wide variety of magnetic configurations, including limiter plasmas if the heating power is sufficiently high. Thus, a divertor configuration seems not an absolute prerequisite, although it enables far easier and very robust access to HDH and allows penetration to very high densities where divertor detachment is well developed /2/. In contrast, evidence is that the EDA H-mode is predicated on a resistive ballooning x-point mode /9/ - which would surely take on different characteristics for the 8-10 x-points of W7-AS and should not even be a factor for a limiter plasma. Hence, the HDH mode may be one of a generic family of “high collisionality” ELM-free H-modes with some form of enhanced (impurity) transport at the edge. Notwithstanding that W7-AS is now decommissioned, hope remains that the extensive HDH-database may yet serve to illuminate the physics base for the HDH H-mode, permitting extrapolation of performance to other machines.

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