H-mode in Helical Devices

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Abstract. L-H transitions and ELMs are observed in all helical devices if operated at relevant plasma conditions thus emphasizing the generic character of these phenomena in toroidal confinement. Particular for helical devices resembling 3D systems is, first, the strong dependency of the H-mode transition and the ELM phenomenology on the magnetic edge configuration and, second, the existence of a sheared radial electric field already before the transition predefined by the ambipolarity condition of the convective fluxes. These elements may constitute biasing preconditions for the spin-up to a high-rotation state.

1. Introduction

L-H transition phenomena - the rapid drop of turbulent transport at the plasma edge followed by the development of steep edge gradients and Edge Localized Modes (ELMs) or ELM-like events - have been observed in all helical devices if operated at the relevant plasma conditions: The low-magnetic shear stellarator Wendelstein 7-AS [1], the heliotrons LHD [2,3,4,5,24] and CHS [6,7] with high shear - negative with respect to the tokamak case - and the helical-axis Heliotron J with negative low shear [8] as well as in the heliac TJ-II with low magnetic shear [9,10,11,12]. For first comprehensive overviews see [13,14]; an H-mode profile database has been launched [15]. To a first approach the classical H-mode and ELMs occur in helical devices with a phenomenology similar to the observations in tokamaks (sect.2), thus confirming the generic character of the underlying plasma edge physics. However, the picture established for the classical 2D tokamak H-mode is supplemented by elements particular for the rich configuration space of 3D magnetic configurations: (1) a strong impact of the magnetic edge topology, the magnetic shear, edge islands, rationals and stochastic regions on the H-mode operational range (sect.3), and (2) the existence of a mean *ExB* flow shear already prior to the transition resulting from the ambipolarity condition of the convective fluxes (sect.4). Both elements are considered to form preconditions for the spin-up of poloidal flows and the associated suppression of turbulent transport (sect.5).

2. quiescent- , ELMy- and High-Density H-modes

After a sudden suppression of edge density- and magnetic turbulence the quiescent H-mode (H*) results in an increase of the edge gradients indicating the set up of a transport barrier in the outermost few cm of the confinement region; an example is shown in Fig.1. ELMs are observed in W7-AS, LHD and TJ-II as well. Particularly large ELMs appear as the termination of quiescent phases with sufficient length. In Heliotron J grassy ELM-like events occur if the absorbed heating power is close to the threshold. Quiescent H-modes suffer from impurity accumulation and radiation whereas grassy ELMy H-modes with good confinement can be maintained stationary at medium power levels [1]. In some cases with steep density gradients Edge Harmonic Oscillations occur with indications for a regulation of particle- [25] and possibly impurity transport [16]. Of particular importance are stationary ELM-less High Density H-modes (HDH, see [1], sect. 6.3) with good energy and very low impurity confinement as obtained in W7-AS by rapidly increasing the edge density starting either from ELMy or from quiescent pre-states. In direct comparison with a preceding H* the HDH regime occurs with a decrease of the *ExB* velocity and an increase of the separatrix density followed by *outflushing* of impurities. The latter as the characteristic property of this regime contradicts the neo-classical expectations, as strong *inward* impurity fluxes are expected for the extremely flat n_e-profiles with steep gradients far outside at the edge where E_r <0. A quasi-coherent mode activity is strictly correlated with the occurrence and disappearance of the HDH regime and thus considered as a candidate for this strong outflushing mechanism [16]. The HDH regime can be accessed in a wide range of magnetic configurations - including various island divertor scenarios and limiter edge - by far exceeding the narrow configuration windows of the quiescent H-mode discussed in sec. 3.2. As impurities do not accumulate on the discharge timescales, stationary discharges at very high densities $\bar{n}$ = 2-4 $10^{20}m^{-3}$ and high heating power are possible. High-density high-confinement regimes are an interesting option towards a helical reactor as the maximum density in helical devices is restricted by the edge power balance only instead of a Greenwald-type density limit [17].

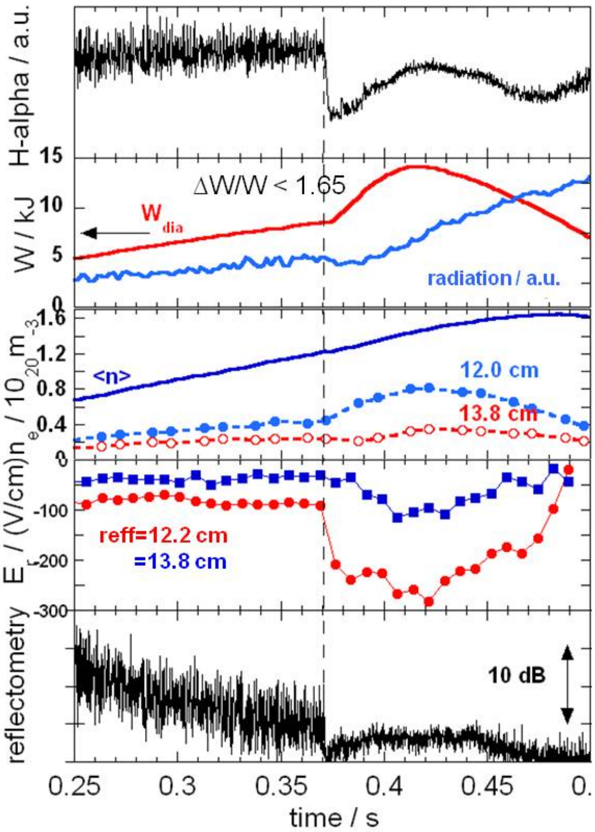

FIG. 1. Example of an L-H-transition in W7AS (from [1]): H_α- signal, diamagnetic energy (red) and radiation (blue), average density (dark blue), and edge densities (close to the separatrix and 2 cm inside), E_r close to the separatrix and 2 cm inside and density fluctuation level (in log scale).

3. Impact of the 3D edge magnetic configuration on H-mode Physics

The influence of the magnetic configuration on the occurrence of the L-H transition is obvious. Moreover the ELMs and ultimately the associated load to the targets can be sensitively controlled by the magnetic configuration [1,3,4,5]. This opens a 3D-specific opportunity for ELM mitigation with possible merit for a reactor concept, albeit in view of steady state divertor operation the magnetic edge configuration is not a fully free parameter. This sensitivity on the magnetic configuration may display stability criteria responsible for the drive of edge instabilities but also indicates the relevance of configuration dependent driving and damping terms to the generation of flows as a decisive element in the transition physics. So far all investigations on the relative relevance of these explanations are based on vacuum magnetic field calculations. Effects resulting from the strong edge pressure gradients such as the pressure induced edge ergodization and bootstrap-currents still have to be included.

3.1 configurations with strong magnetic shear: LHD, CHS

The heliotrons LHD and CHS are characterized by a strong magnetic shear with sign opposite to the tokamak case. The plasma boundary in LHD is determined by a helical divertor edge and develops an ergodic layer in which island structures are embedded (complementary to the poloidal tokamak divertor in the presence of helical magnetic perturbations). The key parameter that controls the H-mode is the vacuum axis position R_{ax} which defines the radial position of the lowest order rational surface $\iota/2\pi$=1. With *large* R_{ax} shifting the m/n=1/1 island right to the plasma edge where it is embeddded in a rather thick ergodic layer a quiescent H-mode with strongly rising density gradients is obtained [24]. With *small* R_{ax} values shifting the 1/1-resonance deep inside the confinement region spontaneous transitions to grassy H-modes are found at relatively high $<\beta>$ ~ 1.5 -2.5% [2]. Also in the Compact Helical System (CHS) the H-mode is obtained with configurations where the plasma axis is shifted to the inboard side constituting a limiter edge, however, easiest access is possible close to a separatrix situation i.e. with R_{ax} as large as possible [7]. In the inward shifted configurations the reminiscence with tokamak limiter H-modes is supported by the observation that the transition is achieved with a threshold power which exceeds divertor tokamak H-mode values by about a factor 1-3 in LHD [5] and a factor of 2 in CHS [7].

3.2 configurations with low magnetic shear: W7-AS, Heliotron J and TJ-II

In low shear devices the vacuum edge rotational transform, $\iota(a)/2\pi$, is chosen as a label for the magnetic configuration where a is the average plasma minor radius. A very pronounced finding is that the quiescent H-mode with a strong gain in confinement occurs in certain windows of $\iota(a)/2\pi$ only (see [1,8,11] and Fig.2). The suspected explanation is that the edge magnetic configuration yields driving and damping terms to the generation of flows. However, their mutual relevance for the L-H transition still needs to be clarified:

(1) Due to the low magnetic shear the radial location of low order rationals at the plasma edge can be sensitively controlled. In TJ-II a high gain in H-mode confinement associated with strong *ExB* flow seem to be triggered if low order rationals are shifted just in the relevant edge layer [11] (see Fig.2, left). Like the relevance of the $\iota/2\pi$=1 surface in the edge layer of LHD this may indicate that the presence of low order rationals favours the spin-up of flows.

(2) In Heliotron J and W7-AS the edge rotational transform determines the topology of the flux surfaces and the separatrix resembling a natural island divertor structure (Fig.2. bottom right). Thereby $\iota(a)/2\pi$ controls the distance between the x-points located poloidally between the island chain right outside the separatrix and the divertor targets. If this distance is small and the connection length decreases down to a value of some metres within a radial distance of Δr~1 cm outside the LCFS only, a strong *ExB* flow shear is measured in W7-AS around the separatrix already at low densities before a quiescent H-mode [19]. For the TJ-II configurations where good H-modes are obtained, such a particularly strong *ExB* shear in L-mode is not found in agreement with the fact that in the TJ-II configuration these dominat edge islands do not exist [12].

(3) Also flow damping may play a role indicated by calculations of the poloidal viscous damping rate for collisional plasmas in W7-AS and Heliotron J which show that in many - but not all - of the relevant $\iota(a)/2\pi$ windows this magnetic pumping has a minimum [18,8].

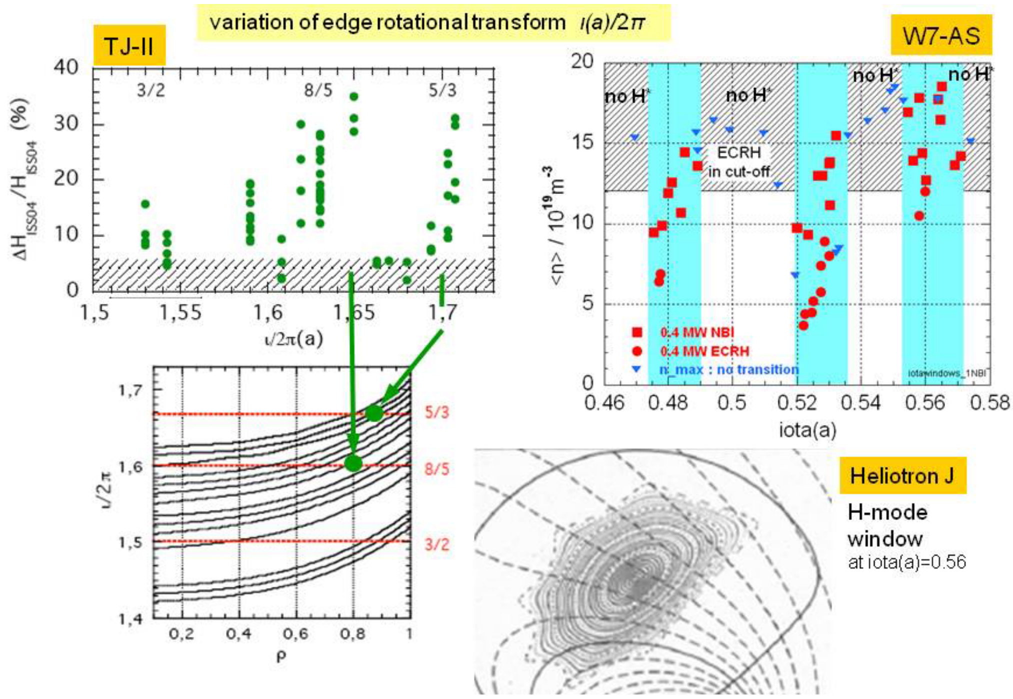

FIG.2. ι(a)/2π dependence of the H-factor in TJ-II (top left) and minimum densities required to reach a quiescent H-mode in W7-AS (top right) showing iota(a) windows with easy access to good H-mode quality. A possible explanation is that for low magnetic shear major rationals can be tuned right in the relevant edge layer as indicated for the TJ-II data on the bottom left. As an example for a magnetic configuration within an H-mode window a Poincare from Heliotron J is shown on the lower right.

The low shear devices reach the L-H transition already at constant low to moderate heating power by increasing the density - in contrast to high shear magnetic configurations both in heliotrons and in tokamaks. Heliotron J demonstrates no significant dependency on power provided a threshold density is exceeded [8]. In TJ-II where no dedicated power scan was possible so far, the transition is reached at moderate low input power P_{abs} close to those expected from Tokamak H-mode scaling P_{abs}/P_{th}=1.0-1.3 [19]. For W7-AS an operational diagram is shown in Fig.3 selecting a magnetic configuration where a quiescent H-mode can be reached: Already for low densities and low absorbed power ELMy states and even short interspersed H* phases (duration ≈ 1ms) are possible. Increasing the heating power needs an increasing density to stabilize the ELMs and allow for a quiescent H-mode (Fig.3, dark blue signs). At a given density a quiescent H-mode therefore can be achieved only *below* and not above a certain power value; this being in clear contrast to the tokamak power threshold (also included in Fig.4 for reference as a dashed line). A transition to a quiescent H-mode is already obtained with ECRH heating as low as 300 kW at a density $\bar{n} = 8.9 \times 10^{19}$ m^{-3}. In such cases the power flux across the separatrix is about a factor of three lower than calculated from tokamak power threshold scaling [19].

4. mean ExB flow shear as a precondition in 3D helical devices

Plasma mean *ExB* flow in 3D helical devices is not a free parameter but already predefined by the ambipolarity condition of the convective neo-classical radial fluxes. At the plasma edge for sufficiently steep gradients of n_e and T_i inside the last closed flux surface the so-called ion-root conditions with negative E_r are realized. In agreement with these expectations - and in contrast to tokamaks - a layer of (sheared) negative E_r is observed inside the last closed flux surface already *before* the L-H transition. This mean shear flow may constitute biasing preconditions for the further spin-up of flows at the L-H transition - as demonstrated also by externally imposed E_r shear in Heliotron J and TJ-II [22,23] - and itself regulates edge transport. A pronounced example for the latter is the so called Optimum Confinement state in W7-AS which can be realized in a wider range of magnetic configurations than the classical H-mode ([1] sect. 5.3). For low to moderate edge densities (low recycling) and sufficient ion heating both, broad T_i-profiles and a strong *mean ExB* flow shear develop together with increasing profile gradients and *without* sudden turbulence suppression as it is a characteristic for the classical L-H transition. Instead this edge transport barrier shows of moderately reduced turbulence level, reduced edge transport and even small ELM-like phenomena.

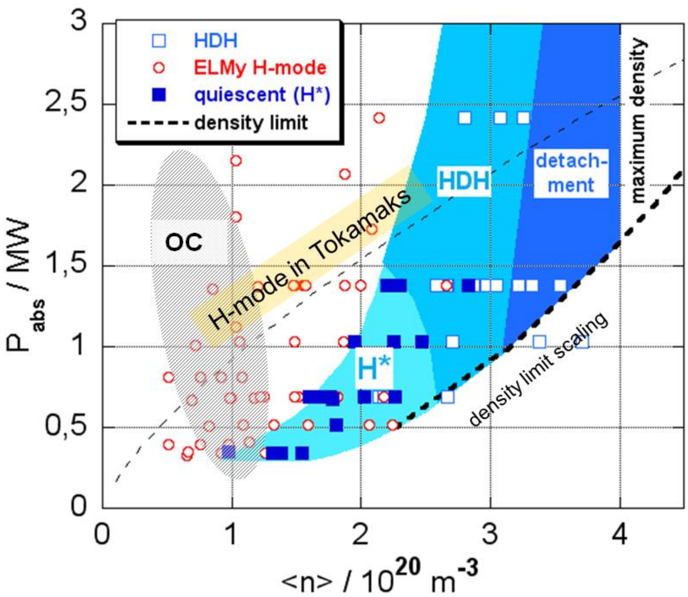

FIG. 3. W7-AS H-mode operational space selecting a configuration with 5/9 island divertor. Absorbed power versus average density derived from both, density ramp experiments and under stationary conditions. Squares indicate ELM-less H-mode, circles ELMy H-modes. The grey shaded area indicates for which conditions the OC regime (see sect. 3) often characterized by grassy ELM-like events can develop, however, taking into account a wider range of configurations. The thin hatched line gives the corresponding tokamak H-mode power threshold obtained from [20].

In contrast the classical H-mode shows a fast bifurcation character demonstrated by the existence of sharp forward- L-H and H-L back-transitions. Immediately *after* the L-H transition marked by the abrupt strong (up to about an order of magnitude) suppression of turbulence the well in negative E_r deepens and pressure gradients increase at the same radii where the turbulence disappeared (W7-AS: [13], TJ:II: [21]). Finally in the fully developed H-mode an *ExB* velocity shear layer with negative E_r is observed in all helical devices (Fig.4). The flow is much higher than expected from the evolution of the pressure gradient $\nabla p_i/(e \cdot n) = E_r$ alone (W7-AS: [1], TJ-II: [9]). This continued *poloidal* v*xB flow*, is in contrast to tokamaks where in the fully developed H-mode in the radial force balance $E_r = \nabla p_i/(e \cdot n) - B_\theta \cdot v_\phi + B_\phi \cdot v_\vartheta$, E_r is balanced by the pressure gradient (first term) alone and v*xB* flows play the role of a trigger only. Note that in helical devices toroidal rotation, $B_\theta \cdot v_\phi$, is damped by the strong helical and mirror terms in the magnetic field spectrum and may be neglected.

As a general observation - both in stellarator and tokamak L- *and* H-mode - edge density turbulence measured with Doppler reflectometry propagates with $v_\perp$ close to the *ExB* velocity derived from spectroscopy and HIBP, at least on the 1ms timescale of the spectroscopic E_r measurement (see e.g. W7-AS, TJ-II and the tokamaks ASDEX Upgrade, Tore supra and TEXTOR). Thus the observed *ExB* shear flow corresponds to a sheared flow of turbulence in the electron diamagnetic direction.

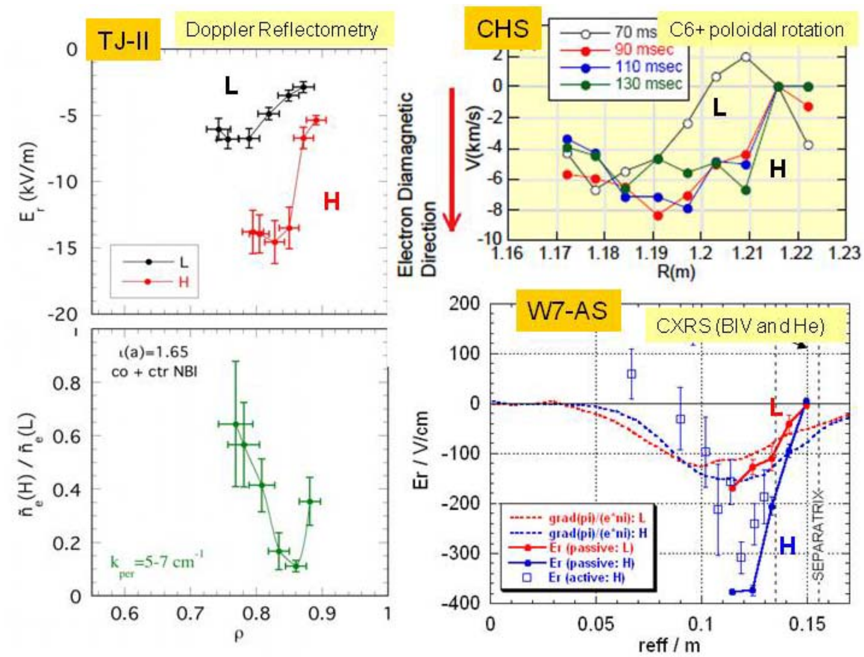

FIG. 4. Negative values of E_r with a sheared mean ExB flow exist already prior to a transition to the H-mode (from [10, 28,13]). After the transition this well in E_r deepens right where the turbulence is suppressed (for example see the turbulence reduction in TJ-II, botttom, left)

The H-L back transition is better suited for detailed investigations as the transition is usually less masked by dithering or ELMs. Measurements at W7-AS [24] show that after heating has been terminated and thus the value of E_r generally decreases, the H-L transition on top of this development is marked by an additional jump of the local E_r by about 90 V/cm within the resolution of the spectroscopy diagnostic (about 1ms). In this device L-H and H-L transition occur with no hysteresis at the same value of the mean *ExB* flow shear, typically E_r' about 50-100 V/cm^2. At TJ-II [10] values for E_r' are significantly lower (10-20 V/cm^2). Besides, the local E_r rather than E_r' evolves towards a transition indicating that other control parameters for the transition must be involved. This is also highlighted by the observation that in W7-AS Optimum Confinement dischargers the mean *ExB* shear flow reaches values that exceed those at the L-H transition by up to a factor of 2.5 but without reaching sudden transition.

5. dynamic sheared flows

On a fast timescale the propagation velocity of density perturbations perpendicular to the magnetic field $v_\perp$- resembling the *ExB* velocity - and the perturbation amplitude have been derived simultaneously from Doppler reflectometry (Fig.5). Pronounced correlated oscillations (order of a few kHz) are observed in both quantities or in the shear of $v_\perp$ respectively. They may display zonal flow structures, a conclusive result, however, requires confirmation by measuring the toroidal/poloidal structure of these modes. At TJ-II (Fig.5, left) the oscillations start at the L-H transition right as the turbulence amplitude breaks down; the relation between oscillations in density fluctuation level and flows is under study [10,12]. Furthermore, long-range correlations in potential fluctuations - as a fingerprint of low frequency oscillating flows - are present already during the development of the mean shear flow at the edge prior to the transition and are amplified either by externally imposed radial electric fields [26] or when approaching the L-H transition [27]. The amplification of zonal flow fingerprints by externally imposed radial electric fields has been observed both in tokamaks and stellarator devices (TJ-II, TJ-K, TEXTOR) suggesting that mean sheared flows stimulate the amplification for turbulence driven zonal flows. In W7-AS (Fig.5, right) both - turbulence amplitude and propagation velocity - change at the H-L (back)-transition on a timescale of about 200 µs between a high-rotation and a low-rotation branch superposed with the oscillations which in W7-AS exist in both modes [24]. The fast timescale of the bifurcation is confirmed by small scale magnetic turbulence where amplitude rises by more than an order of magnitude within 80µs - a timescale also observed for the onset of ELMs [1]. Altogether the observations would support the paradigm that at the classical H-mode transition on top of the developing mean shear flow fluctuating flow structures in interaction with turbulent transport-carrying vortices generate the transition between the low-rotation and the high-rotation state of the plasma edge.

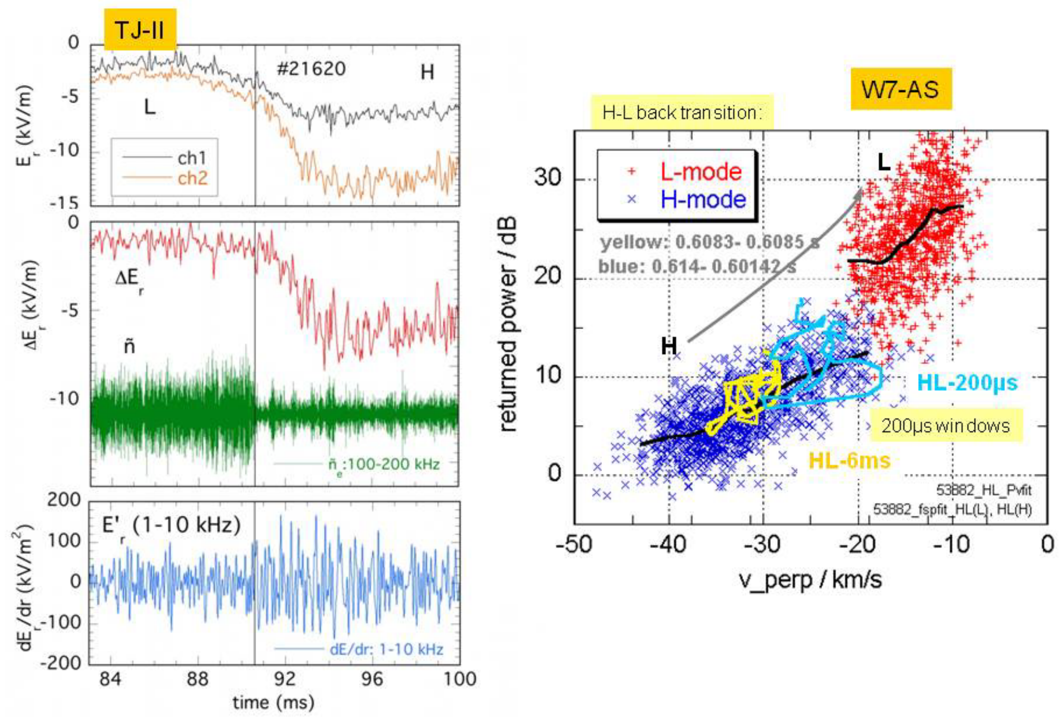

FIG.5. Dynamic sheared flows observed close inside the separarix with Doppler reflectometry (data from ~20ms time intervals, resolution 5-13 µs): In TJ-II (left, from[10]) the ExB shear is derived from two channels with radial distance of about 1cm (top frame). The mean ExB flow shear increases only after the transition marked by the sudden suppression of turbulence (central frame). Right after the transition coherent flow oscillations are observed (bottom frame). Density turbulence amplitude is plotted versus v-perp for an 20ms time window at the H-L back transition in W7-AS (right, from[24]) An H- and an L-mode branch exist, overlaid with correlated oscillations of n-fluct and v_perp. Time traces for two 200 µs interval samples are shown which are taken 6ms (yellow) and 200µs (blue) prior to the H-L back transition respectively.

6. Conclusion and Outline

H-mode is a generic element of toroidal confinement. In helical devices its dependency on the 3D magnetic configuration is obvious. The diversity of available 3D magnetic configurations allows to adress physics elements of H-mode phenomena, to study ELMs, their mitigation as well as ELM free variants and yields operational freedom if these elements are understood. Necessary tools are edge diagnostics for the relevant parameters - profile gradients, flows, turbulence - with sufficient spatial and temporal resolution and accompanying 3D codes for equilibrium, stability and flow investigations to assess on the relevant elements that drive and regulate turbulent transport.

The shear flow investigations so far performed in W7-AS and TJ-II support the current paradigma that the decorrelation of turbulent eddies by sheared - mean and fluctuating - flow structures constitute the elements for the suppression of edge transport. In 3D the mean *ExB* flows are predefined by the ambipolarity condition for the convective fluxes. Improved edge confinement exist which seems to be based already on these mean flows. The classical H-mode is considered as a fast bifurcation phenomenon associated with dynamic (zonal) flows *on top* of (and possibly biased by) the equilibrium mean shear flow conditions at the plasma edge. As a guiding hypothesis in helical devices these spin-up of flows may be biased (or damped) by the specific flow conditions in the 3D magnetic configuration - low order rationals positioned right in the edge layer, the presence of a 3D shaped separatrix defined by edge island which favour potential conditions with an *ExB* shear but also create magnetic pumping and by ergodicity.
H-mode physics may become of increasing importance for the next generation of helical devices as the guidelines of quasi-symmetry and drift optimization developed to reduce neo-classical convective core transport and improve stability, coincide with elements - such as the minimization of geodesic curvature - that are expected to regulate the system of flows interacting with turbulence also. The easy access to H-mode for certain configurations of W7-AS and the high continued v*xB* rotation in the H-mode of W7-AS and TJ-II may be first examples of such a configuration biased transition to a high-rotation state. However, H-mode is not desirable per se - a step towards high density steady-state operation needs its integration with divertor- and plasma core compatible energy-, particle- and impurity fluxes.

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