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Dynamics of poloidal flows and turbulence at the H-mode transition in W7-AS

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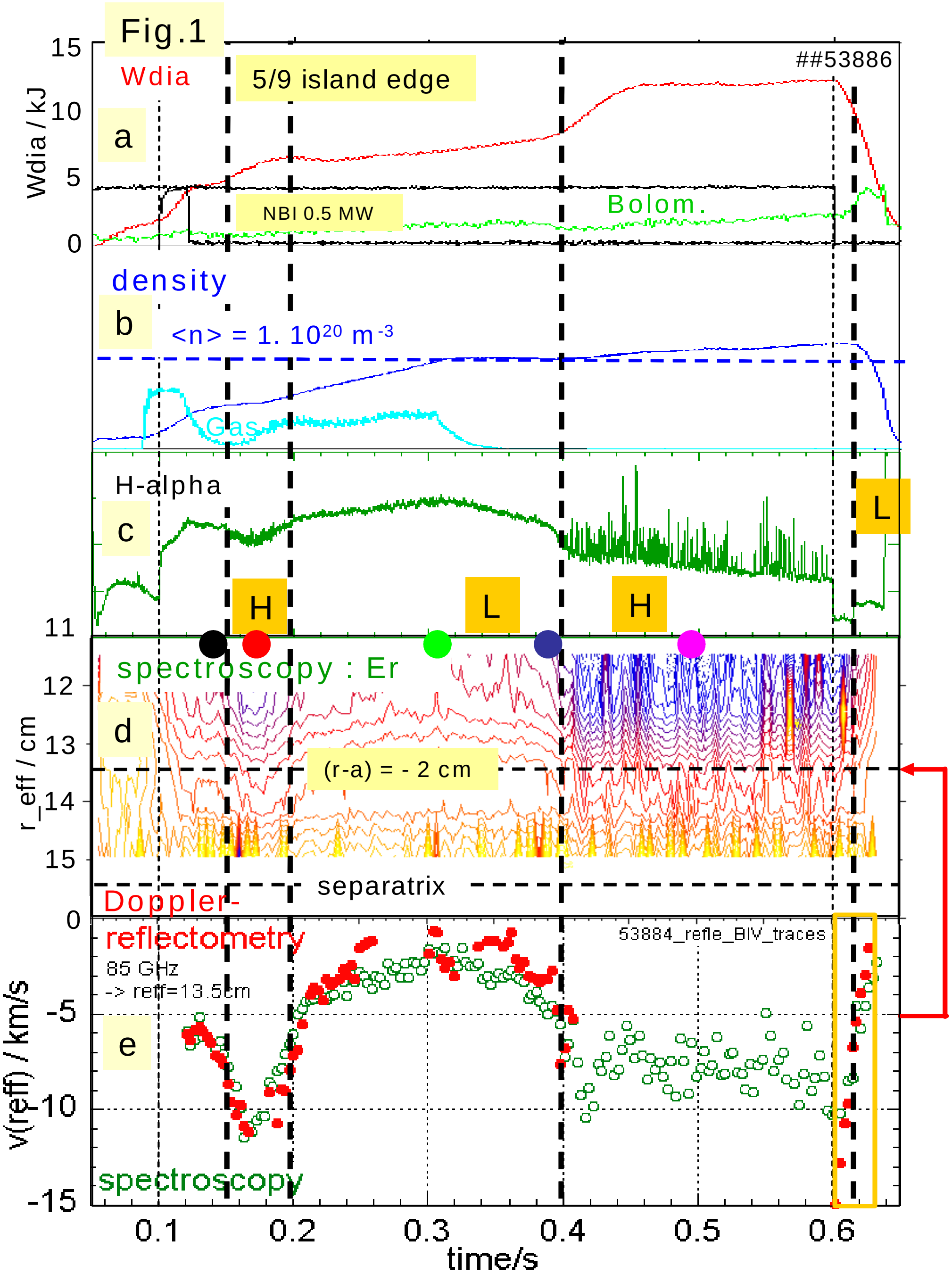
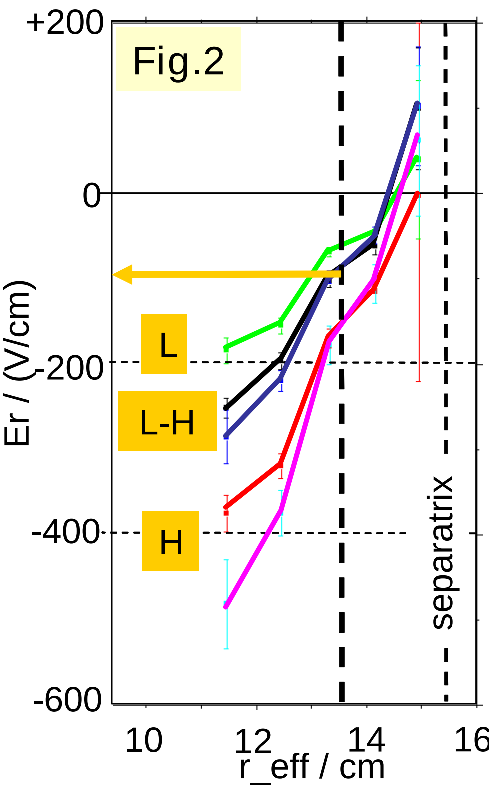
In W7-AS the quiescent H-mode degrades within 50 to 100 ms due to the strongly reduced impurity transport and subsequent increase of radiation. In contrast H-modes with small grassy ELM activity can be maintained nearly stationary while $\Delta W/W \cong 0.6$ with respect to the preceding L-state (Fig.1a). Such scenarios allow to investigate the transition to this H-mode as well as the back-transition both starting from quasi stationary plasma conditions. In the discharge shown the density is ramped to a value close to conditions where a quiescent H-mode can be reached (Fig.1b). In the subsequent density flattop of the average density with reduced gas flux the profile $n(r)$ develops shifting the maximum of ∇n_e inward to the first few cm inside the separatrix (not shown in the Fig.) until after about 100 ms an ELMy H-mode sets in (Fig.1c). The overall development of the radial electric field $E_r(t)$ (from passive spectroscopy using Boron as tracer) right inside the plasma boundary is shown as a contour plot in Fig.1d. Profiles of E_r at selected time points (marked by the colored dots in Fig.1) are shown in Fig.2: The W7-AS stellarator develops a radially sheared negative radial electric field at the plasma edge already from the very begin of the discharge. In general it can be described by the ambipolarity condition of the (however small) neoclassical component of particle fluxes [Baldzuhn J et al 1998 PPCF 40 p967].

The propagation velocity of the turbulence $v_\perp$ - and thus its radial shear $\nabla v_\perp$ responsible for a possible shear flow decorrelation of the turbulent eddies - tightly follows the $E \times B$ velocity $v_{E\times B}$ [see also Hirsch et al. 2001, PPCF 43 p1641]. This is demonstrated by Fig.1e which shows the temporal development of $v_\perp(t)$ at a position about 2 cm inside the separatrix together with $v_{E\times B}(t)$ obtained from spectroscopy. As the radial position of the layer probed with the reflectometer shifts slightly with the changes in density profile, the required $E_r(r)$ is interpolated from the spectroscopy data to the reflectometry radial position by the aid of $n(r)$ measured with a Li-beam.



Note that even at low densities, i.e. prior to the density ramp, a brief ELMy H-mode develops associated with a strongly negative $v_{E\times B}$. The transitions to the two H-mode phases (Fig.1, dashed lines) are preceded by an the increase of the local $v_{E\times B}$ (see Fig.1d,e). Despite the different plasma densities both occur at the same value of the local $\nabla E_r = 100\ \mathrm{V/cm^2}$ taken at a position 2 cm inside the separatrix (Fig.2, black and blue profile). This indicates the importance of the local $v_\perp$ (respectively $\nabla v_\perp$) rather than the background edge profile parameters. During the second H-phase the Doppler reflectometry data had to be omitted as either the tracer turbulence is completely absent in short quiescent phases or -during an ELM- the probed position is intermittently shifted radially. Once the H-mode is reached a further spin-up of $v_{E\times B}$ in electron diamagnetic direction by about a factor of two is observed (Fig.2: red and pink profile) i.e. a deepening of the well in E_r (Fig.1d). In the radial force balance this decrease in E_r is not balanced by the simultaneously increasing ion pressure gradient term $\nabla p / nq_i$ alone, indicating a spin-up of the poloidal ion fluid velocity (the toroidal component is negligible due to the magnetic ripple).



In order to investigate dynamics of the turbulence propagation velocity (respectively its radial shear) and the turbulence spectrum Doppler reflectometry has been developed in the recent years: It selects electron density perturbations with finite wave vector $K_\perp$ by a line of sight which is non-perpendicular with respect to the reflecting layer. $v_\perp$ is obtained from the Doppler-shift of the returning wave whereas the power of the returning signal is a fast but uncalibrated monitor for the amplitude of the turbulence (i.e. the roughness of the reflecting layer). The Doppler reflectometer at W7-AS with tilt angle $\theta_{tilt} = 14$ deg measures perturbations with poloidal scale length $L_\perp = 2\pi / K_\perp \approx 7$ mm according the Bragg condition. It has been optimized to achieve a temporal resolution of <10 µs, which means that for local $v_\perp = 25$ km/s (typical value at transition) a single spectrum is obtained while 10 cm of turbulent surface passes the antenna spot (diameter about 7 cm) [Hirsch and Holzhauer 2004, PPCF 46 593-609].

Each data point in Fig.3 represents a Gaussian fit to the Doppler shifted spectral feature with a spectrum measured every 4 µs . The chosen time interval with duration 35 ms (see yellow rectangle in Fig.1e) resembles the H to L back-transition which occurs 14 ms after the heating has been terminated. In the degrading H-mode a sufficient turbulence level occurs already prior to the transition (Fig.3 blue data). This is in contrast to the transition into the H-mode where the tracer turbulence disappears completely. Over the whole range of measure propagation velocities the turbulence amplitude increases strongly (note the log scale of the vertical axis) with decreasing $v_\perp$ corresponding to a decreasing $\nabla v_\perp$. This relation is broken at the transition to the L-mode (red data) itself, where a sudden increase of $\tilde{n}$ by about a factor of 10 is observed only. For $v_\perp$ no striking discontinuity is observed. The black lines in Fig.3 are spline fits to the two well separated data samples to guide the eyes. Fig.4 shows the temporal behaviour of $v_\perp$ and fluctuation power selecting a time slice of 2 ms around this back-transition. The increase of $\tilde{n}$ itself lasts about 200 µs (yellow bar). Fluctuation amplitude and propagation velocity show large correlated excursions and often nearly coherent oscillations of $v_\perp$ and $\tilde{n}$. Traces of such oscillations from an other 400 µs interval 4 ms prior to the transition are overlaid as yellow lines in Fig.3. They show that the plasma intermittently nearly touches - but never crosses - the critical condition for the back transition. The dominant frequency of these flow fluctuations is around 10 kHz which corresponds to the Geodesic Acoustic Mode frequency calculated for the conditions at the plasma edge. We speculate that these shear flow fluctuations may be considered as critical fluctuations around the phase transition between high- and low-rotation plasma edge and probably display the nearness of the transition.

Fig.3

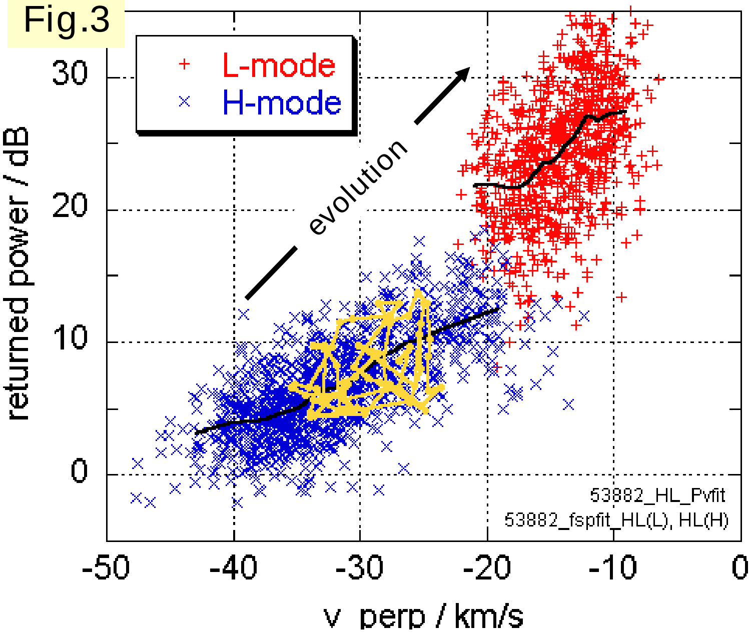


Fig.4