Coupling between turbulence and flows during edge transport barrier formation and collapse

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Abstract

The coupling between sheared flows and density turbulence has been studied experimentally by means of Doppler reflectometry during the L-H and H-L transitions in the TJ-II stellarator. Measurements performed during the L-H transition indicate that the mean sheared flow is not the unique element to explain the suppression of turbulence, oscillating sheared flow has to be also considered. At the H-L back transition, the spatio-temporal evolution of turbulence and flows shows signatures of spatial spreading of the turbulence.

Introduction

The Doppler reflectometry technique allows measuring the spatio-temporal evolution of the density turbulence and its perpendicular rotation velocity what provides information on the radial electric field, Er, and Er-shear. In particular, the Doppler reflectometer of the TJ-II stellarator [1], carefully designed to fulfil the optimization requirements for a good spectral resolution, has been used to measure these magnitudes during L-H and H-L transitions. In TJ-II, L-H transitions are achieved in NBI heated plasmas [2]. Abrupt as well as gradual transitions can be realized depending, among other plasma parameters, on the heating power and magnetic configuration topology. During the H-mode, impurity accumulation and the concomitant increase in radiation losses eventually brings the plasma into the H-L back-transition conditions. The present report summarizes the work already reported in Refs. [3] showing the relation between sheared flows and turbulence measured at the L-H and H-L transitions.

Experimental results

Experiments have been carried out in the TJ-II stellarator in pure NBI-heated plasmas with line-averaged densities $\langle n_e \rangle = 2 - 4 \times 10^{19}$ m^{-3} and electron temperature $T_e = 300 - 400$ eV. Experiments performed with 900 kW of NBI power have shown that, at the L-H transition, E_r becomes more negative and a pronounced E_r-shear develops together with an abrupt reduction in plasma turbulence. The time evolution of both, E_r-shear and density fluctuations, indicates that the reduction in density fluctuations precedes the increase in the mean E_r-shear but is simultaneous with the increase in the low frequency oscillating sheared flow [2]. These observations

are consistent with L-H transition models based on zonal flows. In these experiments the turbulence reduction occurs simultaneously within the radial range covered by the reflectometer and no signatures of radial spreading of the turbulence have been found so far.

The behaviour of density turbulence and flows at the H-L back-transition shows different features as compared to the L-H transition. Moreover, different behaviour is found when exploring radial positions at both sides of the E_r-shear position or further inside the plasma column. An example is shown in figure 1. Figure 1.a shows the time evolution of line-averaged density, plasma energy content and H_α signal as the plasma approaches the H-L back-transition. Several milliseconds before the H-L back-transition the plasma energy content declines as a consequence of the increase in impurity radiation losses. The evolution of E_r measured at different radial positions is shown in figure 1.b. Outside the E_r-shear position, E_r gradually decreases without any discontinuity at the back-transition (top trace in figure 1.b). However, a fast drop in E_r is measured at the back-transition at inner radial positions. Figure 1.c shows the evolution of the density fluctuation level. Close to

Figure 1: (a): The time evolution of plasma density, energy and H_α (b) E_r and (c) $\tilde{n}_e$ measured, from top to bottom, at $\rho - \rho_{shear} = +0.01$, -0.01, -0.03, -0.06 and -0.07. The vertical line indicates the H-L back transition.

the E_r-shear layer position, a sudden increase in the density fluctuation level takes place at the back-transition (three top traces in figure 1.c, measured at $\rho - \rho_{shear} = +0.01$, -0.01, -0.03, respectively), which is not observed further inside the plasma column (two bottom traces measured at $\rho - \rho_{shear} = $ -0.06, -0.07). There, the turbulence level gradually increases as the plasma approaches the back-transition conditions, reaching values right before the back-transition as high as those shown in the L-mode. The radial profiles of E_r and turbulence reduction are shown in figure 2.a and 2.b, respectively. Before the back-transition the E_r profile gradually evolves with a reduction in the E_r-shear of about 20%. Right at the back-transition the E_r-shear vanishes in a time scale of the order of 100 μs.
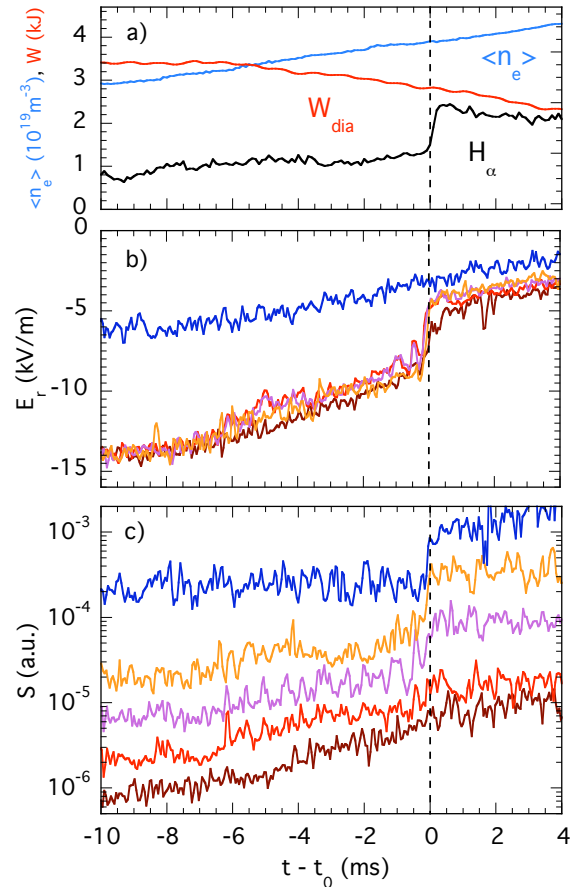
The evolution of the turbulence reduction pro-
file (figure 2.b) clearly shows the distinctive be-
haviour of the density turbulence at both sides of
the E_r-shear layer location. At each radial posi-
tion, one millisecond length time windows are
used to calculate the average fluctuation level
which is then normalized to the fluctuation level
measured at the L-mode. While a gradual in-
crease in the turbulence level is measured at
the inner radial positions, no change in the tur-
bulence level is measured outside the E_r-shear
layer location as the plasma approaches the H-L
back-transition. These experimental results may
suggest the following scenario: Radial spreading
of the turbulence, braked during the H-mode by
the high E_r-shear, becomes noticeable as E_r de-
clines and produces a gradual increase in the tur-
bulence level at the innermost radial positions,
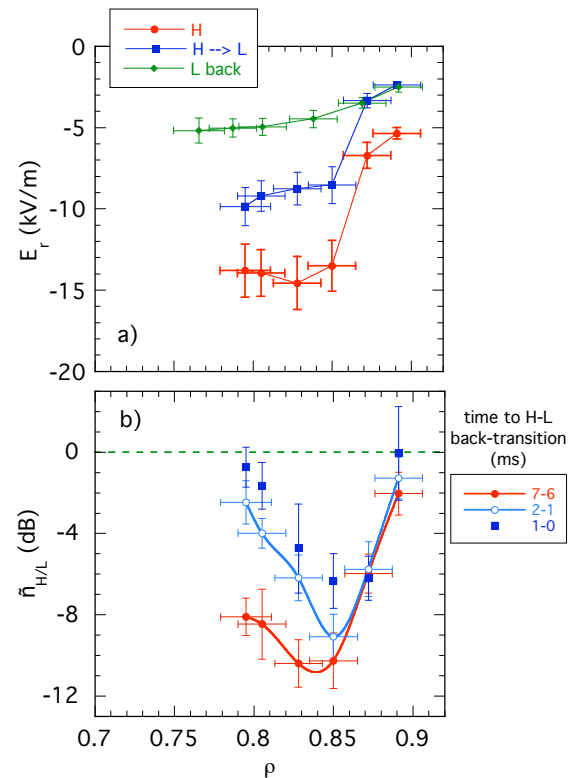reaching the E_r-shear location right before the

Figure 2: (a): E_r profile during the H-mode
(red), right before the H-L transition (blue)
and at the L-mode (green). (b): Evolution of
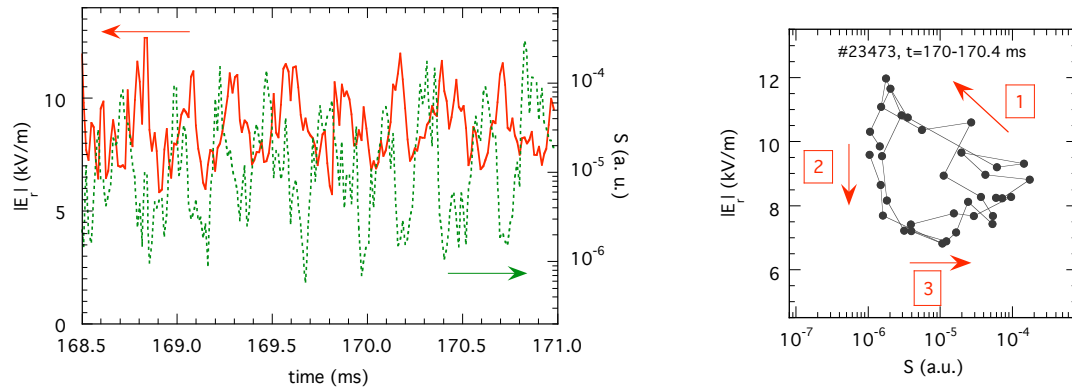turbulence reduction profile.

H-L back-transition. The consequence is a gradual retreat of the transport barrier cuantified as
the width in the turbulence reduction region. The reported results point to the possible role of
radial spreading of turbulence in determining the width of transport barriers.

Close to the L-H transition threshold, pronounced oscillations in both, E_r and density fluctua-
tion level, are measured within the radial range $\rho \approx 0.7 - 0.83$ that are not detected at $\rho > 0.83$.
Differences in the amplitude and duration of these oscillations are found associated to different
magnetic topologies and/or heating power. The oscillations appear right at the L-H transition
and often vanish a few milliseconds later giving rise to subsequent increase in E_r and reduction
in the fluctuation level. However, in some configurations the oscillations last for longer time
periods giving rise to smoother transitions with lower confinement enhancement. A detailed
analysis of the Doppler reflectometer signals shows an interaction between flows and turbu-
lence. The time evolution of E_r and density fluctuations is shown in figure 3.left. Note that a
very short time interval is selected in order to follow distinctly few oscillation cycles. The time
evolution of both, E_r and density fluctuations, reveals a characteristic predator-prey relation-
ship: a periodic behaviour with E_r (predator) following the density fluctuation level (prey) with

Figure 3: Left: Time evolution of E_r and $ñ_e$. Right: Relation between E_r and $ñ_e$

90° phase difference can be clearly seen.

The relation between E_r and the density fluctuation level showing a limit-cycle behavior is represented in figure 3.right. For the sake of clarity, only two cycles are displayed. The turbulence induced sheared flow is generated causing a reduction in the turbulent fluctuations (**1**), the subsequent drop in the sheared flow (**2**) and the posterior increase in the turbulence level (**3**). Further experiments have been carried out to study the dependence of the predator-prey characteristics on different plasma parameters. At fixed magnetic configuration and NBI heating power, the repetition frequency of the predator-prey phenomenon decreases as

Figure 4: Repetition frequency dependence on plasma density measured during different discharges

the plasma density rises. Figure 4 shows the repetition frequency measured as the density rises in several similar discharges. Besides, as the plasma density increases and the repetition frequency drops, the E_r oscillation amplitude decreases while that of $ñ_e$ increases.
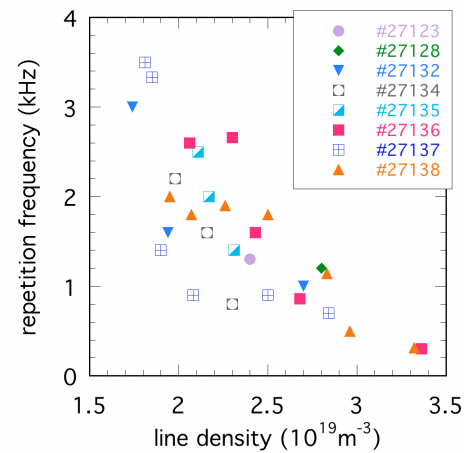
The coupling found between fluctuations and flows, described as a predator-prey evolution, is the basis for some bifurcation theory models of the L-H transition based on turbulence driven zonal flows [4].

References

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