L-H transition experiments in the TJ-II stellarator

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Abstract. The dynamics of turbulence and plasma flows has been studied experimentally by means of Doppler reflectometry during the transition from low to high confinement mode in the stellarator TJ-II. Close to the transition threshold, gradual transitions are achieved showing an intermediate, oscillatory transient phase that facilitates the study of the mechanisms involved in the transition. A coupling between sheared flows and turbulence level is measured which reveals a characteristic predator-prey behavior consistent with the L-H transition models based on turbulence driven flows.

1. Introduction

The high confinement mode (H-mode) regime has been extensively studied since its discovery in the ASDEX tokamak [1]. Theoretical and experimental investigations have accumulated substantial evidence to show that turbulence de-correlation by sheared flows is the mechanism that leads to a strong reduction in turbulence and the formation of transport barriers. This mechanism was proposed in 1990 [2] and confirmed experimentally in the DIII-D tokamak [3]. At present most experimental evidences strongly support the paradigm of sheared electric field suppression of turbulence to explain the H-mode reduced transport [4]. More recently, the relevance of zonal flows on turbulence regulation and formation of transport barriers has been identified [5-7]. Although remarkable progress has been made in understanding the suppression of turbulent transport by sheared $E\times B$ flows, the underlying mechanism that generates sheared electric fields is a fundamental open issue.

Bifurcation theory models, based on the coupling between turbulence and sheared flows, describe the L-H transition passing through an intermediate, oscillatory transient stage [8]. These models consist of coupled evolution equations for turbulence, mean sheared flow and pressure gradient. Using the input power as a control parameter to grow the pressure gradient, these dynamical systems evolve from L-mode to a transient oscillatory stage and finally to H-mode. By increasing the pressure gradient, the instability grows until it is damped by the self-generated sheared flows. The transition occurs when the turbulence driven sheared flow is high enough to overcome the flow damping. As it is discussed in [9], by including the evolution of zonal flows self-consistently, the critical input power for the transition is lowered. Zonal flows trigger the transition by regulating the turbulence until the mean shear flow is high enough to damp both turbulence and zonal flow. Due to the self-regulation between turbulence and flows, the transition is marked by an oscillatory behavior with a characteristic predator-prey relationship between turbulence and sheared/zonal flows.
This intermediate oscillatory transient stage has been barely seen in the experiments; in general, the L-H transition takes place quickly precluding the study of the transition mechanisms.

In the stellarator TJ-II, spontaneous L-H transitions are achieved in Neutral Beam Injection (NBI) heated plasmas [10]. Abrupt as well as gradual transitions are achieved depending, among other plasma parameters, on the heating power and magnetic configuration topology.
Due to the time and spatial scales involved in the transition physics, specific experimental techniques are required to experimentally investigate the turbulence and sheared flows dynamics. In TJ-II, a two-channel Doppler reflectometer is used that allows the measurement of the perpendicular rotation velocity, radial electric field, E_r, E_r-shear and density fluctuations on various scales with good spatial and temporal resolution [11].

The present work, extending the results discussed in [12] reports on the coupling between sheared flows and turbulence measured at the L-H transition in TJ-II. The dynamics of sheared flows and density fluctuations reveals a characteristic predator-prey behaviour, consistent with the L-H transition models based on turbulence driven flows.

2. Experimental Results

Experiments have been carried out in the TJ-II stellarator (magnetic field B = 0.95 T, plasma minor and major radius $a \leq 0.22$ m and R = 1.5 m, respectively), in pure NBI-heated plasmas (line-averaged plasma density $\langle n_e \rangle = 2\text{-}3 \times 10^{19}$ m^{-3}, central electron temperature T_e = 300-400 eV). TJ-II has a low, negative magnetic shear and the possibility to modify the rotational transform.
H-mode transitions reproduce common features found in other devices: an increase in plasma density and plasma energy content, a reduction in H_α signal, the development of steep edge density gradients and a reduction in the turbulence level.
TJ-II experiments performed using the full available NBI power to heat the plasma ($P_{NBI} \leq$ 900 kW) have shown that, at the L-H transition, E_r becomes more negative and a pronounced E_r-shear develops together with a reduction in plasma turbulence at normalized plasma minor radius $\rho \approx 0.85$. 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 [10]. These observations, together with the amplification of long-range spatial correlation in the potential fluctuations [13] are consistent with L-H transition models predicting plasma bifurcations triggered by zonal flows.

Experiments have been also performed with lower input power levels $P_{NBI} \leq 400$ kW, in which the absorbed NBI power, P_{abs}, estimated using the FAFNER2 code that takes into account shine through, charge-exchange and ion losses, is close to that given by the tokamak H-mode power threshold scaling, P_{th} [14]; the ratio P_{abs}/P_{th} ranging from 1.0 to 1.3. Different magnetic configurations have been explored changing the edge rotational transform $\iota/2\pi$ from 1.5 to 1.75. A dependence of the H-mode "quality" on the magnetic configuration is found [15]. Higher values of the confinement enhancement factor associated with strong $E\times B$ sheared flows are found in configurations with a low order rational close to the plasma edge.

Close to the L-H transition threshold, pronounced oscillations in both, E_r and density fluctuation level, are measured within the radial range $\rho \approx 0.75$ - 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 factor. Two examples are shown in figure 1. This figure shows the time evolution of line-averaged plasma density, plasma energy content, H_α signal, and E_r and density fluctuation level measured at $\rho \approx 0.8$ using the Doppler reflectometer, in two magnetic configurations having $\iota/2\pi$ at the plasma edge 1.63 (figure 1 left) and 1.53 (figure 1 right). In the first case (figure 1 left) only few cycles in both E_r and density fluctuations are detected at the transition, whereas in the second one (figure 1 right) the oscillations last for a longer time period. The frequency of the oscillations ranges between 1 and 4 kHz.
At these plasma densities, the absorbed NBI power is about 250 kW, what results in an energy confinement time of $\tau_E = W_{dia} / P_{abs} \approx 8$ ms [16].

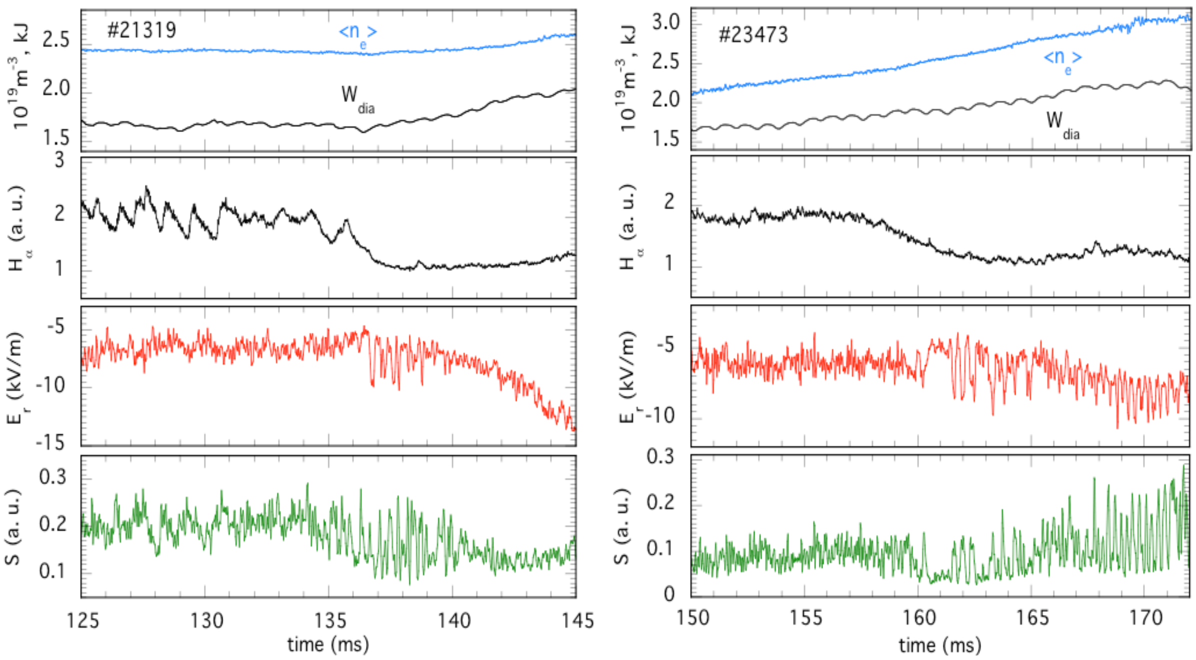

FIG. 1: The time evolution of line-averaged plasma density, plasma energy content, H_α signal, and E_r (in red) and density fluctuation level (in green) measured at $\rho \approx 0.8$ using the Doppler reflectometer, in two magnetic configurations with edge rotational transform in vacuum $\iota/2\pi$ =1.63 (left) and $\iota/2\pi$ =1.53 (right).

These oscillations resemble the so-called IM mode (intermediate confinement mode) of DIII-D [17], however, contrary to DIII-D observations, no signatures of the oscillations appear in the H_α signals in the TJ-II case (see figure 1). Similarly, no oscillations are detected in the evolution of plasma density and temperature, indicating a very small effect, if any, on particle transport. The oscillations do not appear either in the Mirnov coils signals.

A set of reproducible discharges has been realized to characterize the E_r behaviour at different plasma radius positions, in both configurations. The E_r radial profiles in L and H modes are displayed in figure 2. Within the radial range covered by the reflectometer, the E_r profile is rather flat in L-mode in both cases with values close to 5 kV/m. At the transition, in the $\iota/2\pi$ = 1.63 configuration (figure 2 left), E_r increases reaching values as high as 15 kV/m and a pronounced E_r-shear ($\approx$ 600 kV/m^2) develops at $\rho \approx 0.83$ [18]. In the $\iota/2\pi = 1.53$ configuration (figure 2 right) E_r oscillates between $\approx$ 8 and 10 kV/m at $\rho < 0.83$ while remains almost unchanged at $\rho > 0.83$. Consequently, an E_r-shear develops that oscillates between two values $\approx$ 150 and 300 kV/m^2. These values being lower than those measured in the former configuration.

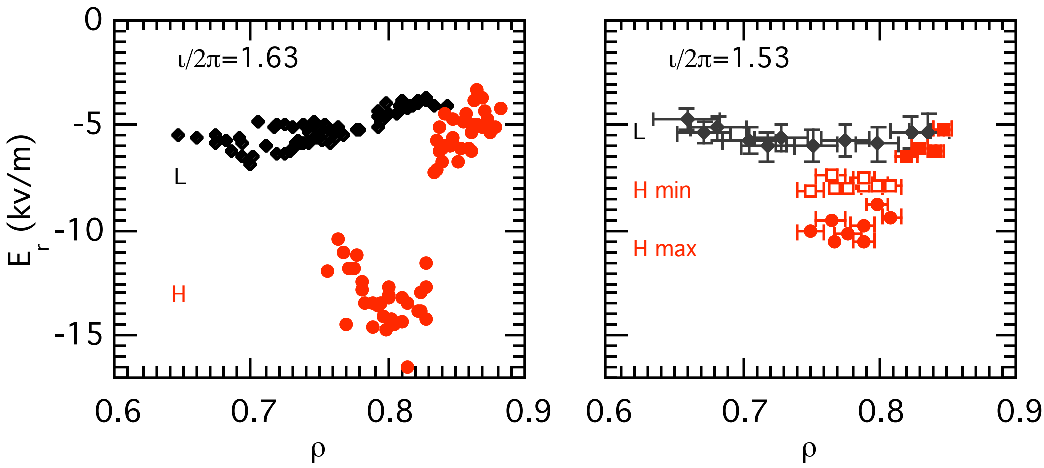

FIG. 2: E_r radial profiles in L and H-mode plasmas in two magnetic configurations with $\iota/2\pi$ at the plasma edge 1.63 (left) and 1.53 (right). En the later case (right), the E_r minima and maxima values measured during the oscillatory phase are represented. No oscillations are seen at the outer radial positions where E_r remains almost unchanged at the transition.

The diamagnetic contribution to the E_r profile has been estimated using the experimental plasma profiles. The diamagnetic term is close to E_r in the L-mode but it changes only very slightly after the transition. This result indicates that a $v \times B$ contribution appears in the H-mode [10], similar to result found in W7-AS experiments [19]. This result is not seen in tokamaks, where in the fully developed H-mode the diamagnetic contribution dominates the radial electric field and the $v \times B$ contribution acts only as a trigger.

A detailed analysis of the time evolution of the Doppler reflectometer signals allows studying the relation between sheared flows and turbulence. This relation is found to follow characteristic predator-prey behaviour.

As an example, a spectrogram of the Doppler reflectometer signals is displayed in figure 3. The contour colour map reflects the amplitude of the Doppler peak, which is proportional to the density fluctuation level, while the frequency of the Doppler peak gives the radial electric field. These magnitudes, obtained by fitting a Gaussian function to the spectra, are shown in figure 4. Note that a very short time interval is selected in order to follow closely and distinctly few oscillation cycles.

The time evolution of both, E_r and density fluctuations, reveals a characteristic predator-prey relationship: a periodic behaviour with E_r (predator, in red) following the density fluctuation level (prey, in green) with 90º phase difference can be clearly seen.

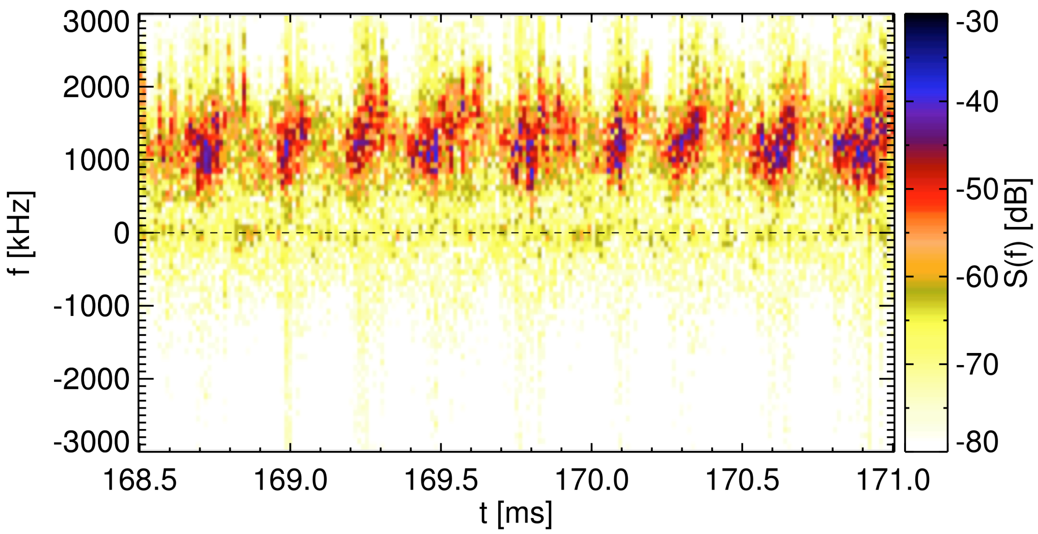

FIG. 3: Spectrogram of the Doppler reflectometer signals measured at ρ ≈ 0.8 in the magnetic configuration with ι/2π = 1.63 at the plasma edge. The colour code reflects the density fluctuation level and the frequency of the Doppler peak gives E_r. A short time interval is displayed in order to follow closely few oscillation cycles.

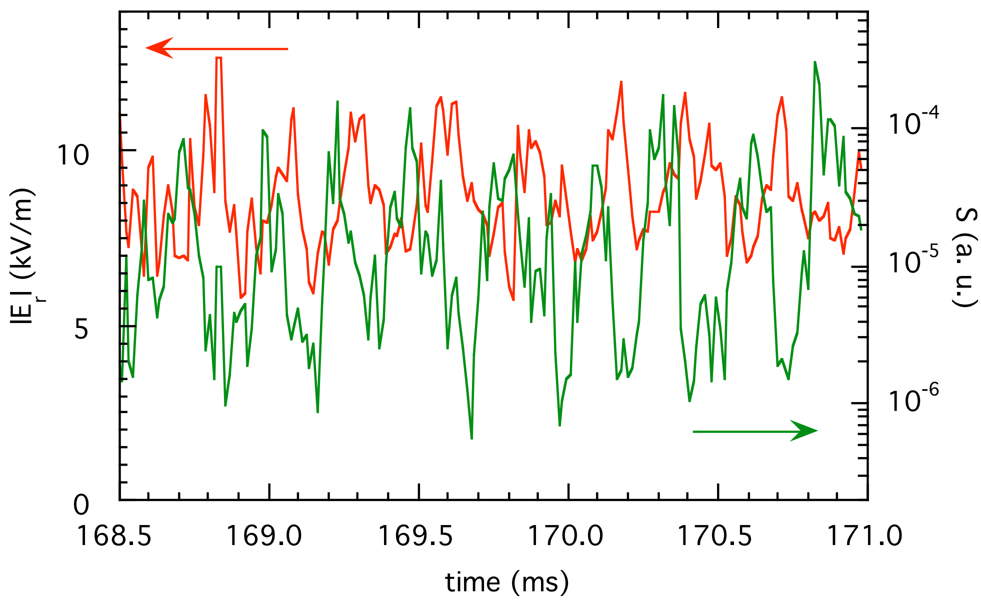

FIG. 4: Time evolution of E_r (in red) and density fluctuation level (in green) obtained by fitting a Gaussian function to the spectra shown in figure 3.

E_r is observed to grow and decay at slightly different time rates ((100-150) μs and (50-100) μs, respectively), while the turbulence grows and decays in comparable times ((50-100) μs). These time scales being much faster than the energy confinement time.

The relation between E_r and the density fluctuation level is represented in figure 5. They evolve following closed trajectories in a limit-cycle style. 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** in figure 5), the subsequent drop in the sheared flow (**2** in figure 5) and the posterior increase in the turbulence level (**3** in figure 5).

As it has been already discussed, the coupling between fluctuations and flows, described as a predator-prey evolution, is the basis for some L-H transition models [8,9]
To our knowledge, this is the first time such experimental evidence is reported supporting the predator-prey relationship of turbulence and flows as the basis for the L-H transition. During the so-called IM mode found in DIII-D power scan experiments [17], the relation between electron temperature fluctuations and sheared flows seems to follow a predator-prey behaviour, however, as the authors explain, the sheared flow is not directly observed but inferred from Beam Emission Spectroscopy data.
Two ingredients have been essential in attaining the results presented in this work, the possibility of achieving gradual L-H transitions and the capability of simultaneously measuring both magnitudes, density fluctuations and sheared flows, with good spatiotemporal resolution.

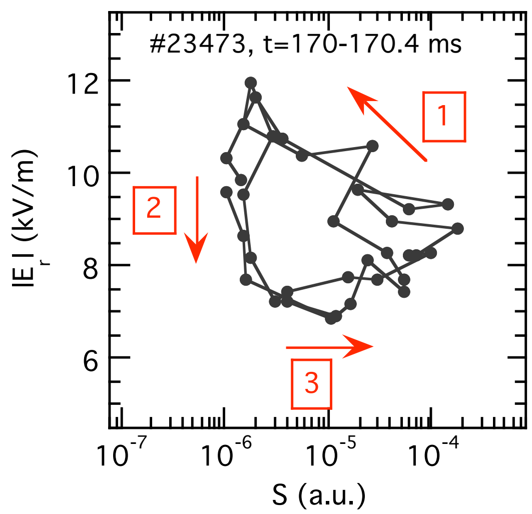

FIG. 5: Relation between E_r and density fluctuation level. They evolve following closed trajectories in a limit-cycle style. Two of the cycles shown in figure 4 are displayed; the time interval between consecutive points being 12.8 μs.

3. Summary and Conclusions

The dynamics of turbulence and flows has been measured during L-H transitions in the stellarator TJ-II. When operating close to the L-H transition power threshold, pronounced oscillations in both, E_r and density fluctuation level, are measured at the transition. The oscillations are measured right inside the $E\times B$ shear layer (located at $\rho \approx 0.83$). The time evolution of both, E_r and density fluctuation level, shows a characteristic predator-prey behaviour, with E_r (predator) following the density fluctuation level (prey) with 90º phase delay. These experimental observations are consistent with L-H transition models based on turbulence induced sheared/zonal flows.

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