Spatiotemporal and spectral structure of the turbulence-flow interaction at the L-H transition in TJ-II plasma

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Abstract:
The physical mechanisms behind the L-H transition have been experimentally studied in the TJ-II plasmas. The spatiotemporal and spectral structure of the interaction between turbulence and flows has been studied close to the L–H transition threshold conditions. The temporal dynamics of the turbulence–flow interaction displays a predator–prey relationship and both, radial outward and inward propagation velocities of the turbulence–flow front have been measured. Moreover, the turbulence scales involved in the energy transfer of the predator–prey process have been identified.

1 Introduction

The High confinement mode (H–mode) regime has been extensively studied since its discovery in the ASDEX tokamak \cite{1}; however, the physical mechanism triggering the H-mode has still not been clearly identified. Bifurcation theory models based on the coupling between turbulence, zonal flows driven by the Reynolds stress, and equilibrium $E \times B$ flow, describe the Low to High confinement mode transition (L–H transition) passing through an intermediate, oscillatory transient stage \cite{2}. Zonal flows trigger the transition by regulating the turbulence until the mean shear flow is high enough to suppress turbulence effectively, which in turn subsequently impedes the zonal flow generation. Due to the self-regulation between turbulence and flows, the transition is marked by an oscillatory behavior with a characteristic predator–prey relationship \cite{3} between turbulence and zonal flows. This intermediate oscillatory transient stage, called I–phase, has been seen in the L–H transition experiments in several devices: NSTX \cite{4}, TJ–II \cite{5}, AUG \cite{6} and EAST \cite{7}. In these experiments, as in the predator–prey theory model \cite{2}, only the temporal dynamics of the turbulence–flow interaction is studied. However, as it has been pointed out in Ref. \cite{8}, where the 0–dimensional predator–prey theory model is upgraded toward a 1–dimensional one, the spatial evolution should also be taken into account as a
necessary step to go towards the L–H transition model. This fundamental issue has been recently addressed in TJ-II [9] and also in DIII-D [10]. Besides, in TJ–II dedicated experiments have been carried out during the last experimental campaign to investigate the spectral structure of the turbulence–flow interaction during the predator–prey process.

In this work, after summarizing the spatiotemporal evolution of the turbulence–flow oscillation pattern (reported in [9]) in section 2.1, some hints on the triggering mechanisms are described in section 2.2 and the spectral structure of the turbulence flow interaction is discussed in section 2.3.

2 Experimental results

The experiments have been carried out in the TJ–II stellarator in pure NBI–heated plasmas (line–averaged plasma density \( \langle n_e \rangle = 2 - 4 \times 10^{19} \text{ m}^{-3} \), central electron temperature \( T_e = 300 - 400 \text{ eV} \)). The NBI input heating power is kept constant along the discharge at about 500 kW but the fraction of NBI absorbed power—estimated using the FAFNER2 code that takes into account shine through, CX and ion losses—increases from 55 to 70% as the plasma density rises. Due to the temporal and spatial scales involved in the L–H transition physics, specific experimental techniques are required to investigate the turbulence and flow dynamics [11]. In TJ–II, a two–channel Doppler reflectometer is used that allows the measurement of the perpendicular velocity and density fluctuations at two radial positions simultaneously with good spatial and temporal resolution [12]. Besides, the Doppler reflectometer offers the possibility to probe different turbulence scales by steering the probing beam [13].

2.1 Spatiotemporal evolution

L–H transitions in TJ–II are achieved in pure NBI heated plasmas under Li–wall conditions. In general, the plasma undergoes a fast direct transition from L to H–mode [11]. However, close to the transition threshold conditions at specific magnetic configurations, the so–called intermediate–phase (I–phase) is observed with pronounced oscillations in both the \( E \times B \) flow and the density fluctuation level, measured right inside the \( E \times B \) shear position [5, 9]. At the transition from the L–mode to the I–phase, the \( H_\alpha \) drops, the plasma energy content and the density increase and the spectrogram of the Doppler reflectometer signals show an increase in the Doppler peak frequency and the onset of the oscillations. The oscillations appear as changes in the intensity and frequency of the Doppler peak, and show a predator–prey relationship between turbulence and flows, with the flow—the predator—following the turbulence—the prey—with a phase delay of 90° as in a limit–cycle. The repetition frequency of the oscillation–pattern drops along the plasma discharge as the line density increases. Besides, as the plasma density increases and the repetition frequency drops, the \( E_r \) oscillation amplitude decreases while that of the density fluctuation level increases. These observations can be explained based on the collisional damping of flows which eventually sets the turbulence level [14, 8]. The radial profile of \( E \times B \) flow changes from a rather flat profile in L–mode in the radial range
from $\rho = 0.60$ to 0.85 to a sheared one during the oscillating I–phase with the $E \times B$ shear located at $\rho \approx 0.82$. In figure 1a the $E \times B$ flow profile measured in L–mode and the extreme values of the flow oscillation measured at each radial position are displayed. The flow oscillation amplitude is about 1 km/s close to the $E \times B$ shear position and increases gradually as inner radial positions are probed. As a consequence, the $E_r$ well of about 10 kV/m measured at the maximum of the oscillations shrinks in each limit–cycle and an inner shear layer is measured at $\rho \approx 0.75$.

![FIG. 1: (a) Perpendicular flow profiles measured at L-mode (black) and during the intermediate oscillatory phase: flow maxima (red) and minima (blue). (b) Radial propagation velocity of the turbulence–flow front measured during the I–phase.](image)

The TJ–II Doppler reflectometer allows measuring simultaneously at two radial positions which can be independently selected [15]. Therefore, it is possible to obtain information on the radial propagation characteristics of the cyclic spatio–temporal pattern. A radial propagation velocity from the inner to the outer radial positions is found in the oscillation–patterns measured from the onset of the oscillations, at line–densities of about $1.8 \times 10^{19} \text{ m}^{-3}$, up to line–densities of about $3.0 \times 10^{19} \text{ m}^{-3}$. At densities above $3.0 \times 10^{19} \text{ m}^{-3}$, in some particular cases the propagation direction eventually reverses after a short time period without oscillations. The analysis of the delays yields propagation velocities within the range $\approx 50 – 200 \text{ m/s}$ with a radial trend as shown in figure 1b. In this figure the vertical bars represent the error in the estimation of the propagation velocity and the horizontal ones represent the radial separation between the two channels in each discharge. The radial propagation velocity decreases as the oscillation–pattern approaches the outer $E_r$–shear position (at $\rho \approx 0.82$).

### 2.2 Triggering mechanisms

TJ–II has a low, negative magnetic shear and the possibility to modify the rotational transform $\iota/2\pi$ within a rather broad range from 0.9 to 2.2. In TJ–II [16], as in other low magnetic shear helical devices [17, 18], the magnetic topology has a sensitive influence on H-mode realization and quality. Also, in TJ–II plasmas the I–phase is observed close to the L–H transition threshold conditions at some specific magnetic configurations. In
these conditions coherent modes associated with low order rational surfaces are often observed with frequencies in the range of 100 kHz. Systematically, the I–phase starts after a decrease of the mode frequency, to values about 40-50 kHz. At the onset of the oscillations in the I–phase the coherent mode vanishes. The mode is detected by several diagnostics including the Doppler reflectometer (provided an appropriated analysis approach is applied [19]), which localizes it at the inner radial positions ($\rho \approx 0.60 - 0.65$).

As an example figure 2 shows the coherent mode, the spectrogram of the Doppler reflectometer signals and the density fluctuation level measured at $\rho \approx 0.65$ and $k_{\perp} \approx 9 \text{ cm}^{-1}$. In the examples shown in this paper the magnetic configuration is fixed with $\iota/2\pi(a) = 1.53$, the rational surface 3/2 being located at the plasma interior. Configurations with different low order rational surfaces as 5/3 or 8/5 also show the I–phase with the predator–prey oscillations [11, 5]. Differences in the amplitude and duration of the oscillations are found associated to the different magnetic topologies; the lower the order of the rational surface, the longer the duration of the I–phase. The mechanism by which the rational surface is triggering or easing the L–I transition may be related to local changes in the radial electric field or in the turbulence that propagates towards the plasma edge driving the plasma to the threshold conditions. Whereas in all cases a spin-up of flows may be linked to the low order rational surfaces, in the lower order rational surface cases, a stronger viscous flow damping may be expected [20] that may delay the I–H transition.

2.3 Spectral structure

The spectral structure of the turbulence–flow interaction has been measured during the intermediate oscillatory phase. To this end, the Doppler reflectometer ellipsoidal mirror tilt angle is scanned in a shot to shot basis to select different turbulence scales; at each tilt angle, measurements at different probing frequencies ensure a densely covered wavenumber–radius space. The wavenumber–radius space covered is calculated using

FIG. 2: From top to bottom: Coherent mode detected by applying the approach described in [19] to the Doppler reflectometer signals, Doppler reflectometry spectrogram showing the increase in the Doppler peak frequency and the onset of the oscillations related to the L to I–phase transition, and the corresponding density fluctuation level, measured at $\rho \approx 0.65$ and $k_{\perp} \approx 9 \text{ cm}^{-1}$. 

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the three-dimensional ray tracing code TRUBA. The perpendicular wavenumber range covered in these experiments is $k_\perp \approx 2 - 15$ cm$^{-1}$ and the corresponding normalized wavenumber range is $k_\perp \rho_s \approx 0.4 - 3.0$, where $\rho_s = \sqrt{2m_iT_e/eB} = \rho_i\sqrt{T_e/T_i}$ is the ion Larmor radius evaluated at electron temperature. The change in the density profile as the plasma evolves from the L-mode to the I-phase implies a modification in the radial region probed by the Doppler reflectometer during the I-phase ($\rho \approx 0.74 - 0.82$) as compared with that covered during the L-mode ($\rho \approx 0.66 - 0.78$).

**FIG. 3:** Density fluctuation wavenumber spectra measured during the L-mode at line averaged central density $\langle n_e \rangle \approx 1.8 \times 10^{19}$ m$^{-3}$ (left) and during the intermediate oscillatory phase $\langle n_e \rangle \approx 2.3 \times 10^{19}$ m$^{-3}$ (right). The extreme values of the turbulence level measured during the I-phase are represented: maxima (in blue) and minima (in red). The spectral indexes are shown for each spectrum and the normalized wave-numbers $k_\perp \rho_s = 1$ and 2 are marked in the figures.

Figure 3 shows the perpendicular wavenumber spectra of the density fluctuations measured during the L-mode, figure 3 left, and during the intermediate oscillatory phase, figure 3 right. During the I-phase, maxima and minima of the density fluctuation level are represented and labeled as $S_{\text{high}}$ and $S_{\text{low}}$, respectively. In all cases, the density turbulence level decreases as the wavenumber increases and two wavenumber regions with different power laws and a well defined knee, can be identified. The spectral indexes and the wavenumber ranges are specified in the figure. A direct comparison between the $k_\perp$-spectrum measured during the L-mode and those measured during the I-phase is not fully meaningful due to the different radial regions of the measurements. In L-mode the spectral indexes are $\alpha = -2.7$ and $-9.2$ in the ranges $k_\perp < k_{\text{knee}} \approx 8.4$ cm$^{-1}$ and $k_\perp > k_{\text{knee}} \approx 8.4$ cm$^{-1}$, respectively. During the I-phase, two different wavenumber ranges are found in the turbulence wavenumber spectra. A flatter wavenumber region is found in both cases at large turbulence scales, up to $k_{\text{knee}} \approx 5$ cm$^{-1}$ in the low turbulence spectrum and up to $k_{\text{knee}} \approx 8$ cm$^{-1}$ in the high one. At the knee the spectral fall-off starts with stronger spectral index in the high turbulence spectrum, $\alpha = -9.6$, as compared to that in the the low turbulence spectrum, $\alpha = -5.6$. The comparison between $S_{\text{high}}$ and $S_{\text{low}}$ shows a rather well defined wavenumber range where the oscillation in the turbulence level is maximum, $k_\perp \approx 6 - 11$ cm$^{-1}$, the corresponding normalized wave-numbers being
$k_{\perp}\rho_s \approx 1.2 - 2.2$. At shorter and longer scales, almost no oscillation in the turbulence level is detected. This is clearly seen in figure 4a where the turbulence level oscillation amplitude, i.e. the difference between maxima and minima, is represented.

These measurements indicate that the relevant turbulence scales involved in the turbulence–flow predator–prey process are the intermediate ones, in the range $k_{\perp} \approx 6 - 11$ cm$^{-1}$. Once the dominant turbulence wavenumber range is identified it is worth studying the behavior of the perpendicular flow measured at the different turbulence scales. The perpendicular flow oscillation amplitude measured at different perpendicular wavenumbers during the I–phase is shown in figure 4b. Whereas very similar values of the perpendicular flow minima are measured at the different turbulence scales, a slight dependence on $k_{\perp}$ is found in the perpendicular flow maxima and therefore in the perpendicular flow oscillation amplitude. This dependence can be used to obtain information on the dispersion relation of the plasma turbulence involved in the predator–prey process which eventually could be compared with theoretical predictions. Still, the slight dependence of the flow oscillation amplitude on the turbulence scale indicates that all turbulence scales follow the flow oscillations although the scales involved in the energy transfer of the predator–prey process are preferentially the intermediate ones.

3 Discussion and conclusions

The spatial, temporal and spectral structure of the turbulence–flow predator–prey interaction has been measured during the I–phase at the L–I–H transition in TJ–II plasmas.

Two distinct spatiotemporal patterns, namely outward and inward propagation, are measured. The outward radial propagation velocity gradually decreases as the oscillation–pattern reaches the $E_r$–shear position. In each oscillation cycle the $E_r$–well shrinks and an inner shear layer develops. A possible explanation for the spatio-temporal evolution of the oscillation–pattern could be linked to turbulent–flow events propagating toward the plasma edge. These events could be generated in the plasma interior due to instabilities linked to the magnetic topology. A coherent mode linked to a low order rational surface is detected at the plasma gradient region right before the onset of the I–phase oscillations.
Local changes in the radial electric field and/or plasma turbulence linked to low order rational surfaces and propagating toward the plasma edge may be figured out as a trigger mechanism for the L–I transition. These observations resemble the results found in a linear plasma device and reported in [21]. Those experimental results show how vortex-like structures propagating towards the plasma edge are slowed down and finally absorbed into the edge shear layer, transferring their momentum and energy to the shear flow which in turn is amplified. The inward propagation velocity of the oscillation–pattern is observed in some particular cases at the final stage of the discharge after a quiet period without oscillations. In those cases the oscillation–pattern arises at the outer shear layer position and propagates towards the plasma interior. Similar behavior has been recently reported in [10], where inward propagation velocities of about 200 m/s are measured inside the separatrix position. The present experimental results indicate that the edge shear flow linked to the L–H transition can behave either as a slowing–down, damping mechanism of outward propagating turbulence–flow oscillating structures, or as a source of inward propagating turbulence-flow events.

The spectral structure of the turbulence–flow interaction has been measured during the I–phase allowing the identification of the relevant turbulence scales involved in the turbulence–flow predator–prey process. The measurements indicate that intermediate turbulence scales within the range \( k_\perp \approx 6–11 \text{ cm}^{-1} \) dominate the process. This intermediate turbulence wavenumber range being the dominant player in the zonal flow generation by Reynolds stress has previously been identified both, experimentally [22, 23] and in simulations [24]. Besides, in previous experiments carried out at TJ–II, a scale–selective turbulence reduction was measured in H–mode in comparison with L–mode [13]. In H–mode, a turbulence reduction in the whole wavenumber range was measured, being more pronounced at intermediate scales. This observation together with the turbulence behavior found during the I–phase, and reported in section 2, are consistent with the bifurcation theory model of the L–I–H transition [2, 8]. At the transition threshold conditions, a zonal flow driven by the turbulent Reynolds stress arises regulating the turbulence and given rise to the turbulence–flow predator–prey interaction. In this I–phase, the turbulence is regulated mainly by the zonal–flow generation which effectively takes place at intermediate turbulence scales. No changes are measured at shorter and longer turbulence scales. As the plasma enters into the H–mode, additional mechanisms like turbulence decorrelation by mean sheared flows may become active affecting a broader range of turbulence scales. A slight dependence of the perpendicular flow oscillation amplitude on the turbulence scale has been measured during the I–phase. This dependence may be used to obtain information on the dispersion relation of the plasma turbulence involved in the predator–prey process which eventually could be compared with theoretical predictions. The results indicate that all turbulence scales follow the flow oscillations although the scales involved in the energy transfer of the predator–prey process are preferentially the intermediate ones. The reported experimental results support the predator–prey theory model of the L–I–H transition. The turbulence–flow front propagation and its interaction with the edge shear flow has been described and the turbulence scales involved in the energy transfer of the predator–prey process have been identified.
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References