Spatiotemporal and wavenumber resolved bicoherence at the L-H confinement transition in the TJ-II stellarator

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Introduction

The spontaneous L-H transition is the subject of intense study in the fusion plasma physics community, due to its relevance for the design of a reactor and its intrinsic physical interest. The currently prevailing theory explains this phenomenon on the basis of a sequence of events, involving zonal flow generation by turbulence via the Reynolds Stress mechanism and the subsequent suppression of the selfsame turbulence, leading to the formation of a steady state sheared flow [1]. The observation of this sequence of events is a challenge.

At the TJ-II stellarator, the L-H transition is studied using a Doppler reflectometer, capable of detecting the advective turbulent velocity at the reflection layer [2]. By scanning the tilt angle of the probing beam in successive, similar discharges, different values of the perpendicular wave numbers can be probed. This allows the study of the interaction between zonal flows and turbulence with (a) spatial, (b) temporal, and (c) wavenumber resolution during the L-H transition [3, 4].

Methods

The TJ-II vacuum magnetic geometry is completely determined by the currents flowing in four external coil sets. Here, we focus on two magnetic configurations having $\iota(a)/2\pi = 1.630$ and 1.553. The experiments have been carried out in pure NBI heated plasmas (line averaged plasma density $\langle n_e \rangle = 2-4\times 10^{19}$ m^{-3}, central electron temperature $T_e = 300-400$ eV). The NBI input heating power is kept constant at about 500 kW.

In this work, we consider two different L–H transition scenarios. Standard or *fast* L–H transitions are observed in the magnetic configuration having $\iota(a)/2\pi = 1.630$ [4], while *slow* transitions are observed in the configuration having $\iota(a)/2\pi = 1.553$ and a low order rational (3/2) at $\rho = r/a \simeq 0.72$. In the latter configuration, the so-called intermediate phase (I), characterized by a predator-prey type interaction between turbulence and flows, appears between the L and H phases [5, 6, 3], which has also been seen in models [7, 8] and on other devices [9, 10]. In both scenarios, spatiotemporal and scale resolved Doppler reflectometry measurements were performed in series of repetitive discharges [4]. Doppler reflectometry allows the measurement of the turbulence fluctuation amplitude $\tilde{n}$ as well as the fluctuating perpendicular flow $\tilde{v}_\perp$, both with good temporal and spatial resolution, making the two main quantities involved in zonal flow dynamics accessible experimentally. In this work, we consider the complex amplitude Doppler reflectometry signal, $Ae^{i\phi} = (A\cos\phi, A\sin\phi)$, which contains information of both the perpendicular flow, $\tilde{v}_\perp = d\tilde{\phi}/dt$, and the density turbulence, $\tilde{n} \propto \tilde{A}$.

Bicoherence

Computing the auto-bicoherence for the complex Doppler reflectometer data around the time of the L–H transition, one typically obtains results such as those shown in Fig. 1. The auto-bicoherence is very significant, as the value is some two orders of magnitude above the noise level. Fig. 1 also shows the cross bicoherence between $\tilde{v}_\perp$ and $\tilde{n}$ for the same discharge. Here, significant coupling is limited mainly to the lines $f_2 \simeq 0$ and $f_2 \simeq \pm f_1$, indicating an interaction between two very similar frequencies f_a, f_b, interacting via a very small difference frequency $f_c = f_a - f_b$. This is in fact what one would expect for the interaction between a zonal flow and turbulence [1, 11]. Although the cross bicoherence between $\tilde{v}_\perp$ and $\tilde{n}$ is easier to interpret, the auto-bicoherence of the complex Doppler reflectometry signal (containing the same information) is easier to compute and yields a larger signal to noise ratio in the total bicoherence value. Therefore, we will use the latter as a generic proxy to study the spatiotemporal evolution of the total bicoherence.

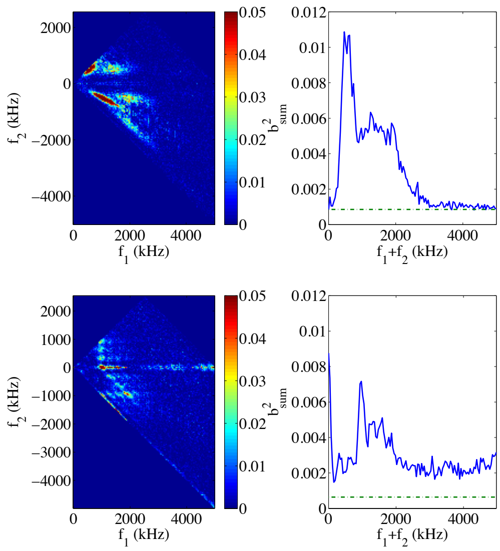

Figure 1: Discharge 22277. Configuration with $\iota(a)/2\pi = 1.704$. Top: Mean auto-bicoherence and mean summed auto-bicoherence of complex Doppler reflectometry channel 1. Bottom: Cross bicoherence between $\tilde{v}_\perp$ and $\tilde{n}$ (Doppler reflectometry channel 1) during the L–H transition ($1100 < t < 1130$ ms, $t_{L-H} = 1116$ ms). The dashed line indicates the noise level.

The fast L–H transition

To study the radial and temporal behavior of the bicoherence across the fast L–H transition, we have analyzed a series of 25 discharges in the same magnetic configuration ($\iota(a)/2\pi = 1.630$). See Ref. [4] for more details about this series of discharges. The Doppler reflectometer probing frequency and tilt angle were varied on a shot to shot basis, and correspondingly the radial position of the reflecting layer and the wave number $k_\perp$. Fig. 2a indicates the evolution of the density profile across the L–H transition. Due to the evolving profile, both the position of the reflecting layer and the wavenumber change as a function of time across the transition [4]. The measured channel locations and wave numbers are shown in Fig. 2b. The ρ and $k_\perp$ values indicated on the axes of Figs. 2c–e correspond to the situation in H-mode.

Figs. 2c–e show the values of the auto-bicoherence $b^2(k_\perp, \rho, \Delta t)$, averaged over $k_\perp$, ρ, and Δt, respectively. It is seen that the bicoherence appears $\sim 20-30$ ms before the L–H transition at a specific radius ($\rho < 0.8$) and that specific perpendicular wave numbers are involved ($k_\perp \simeq 8-11$ cm^{-1}). The bicoherence persists until about $10-20$ ms after the L–H transition.

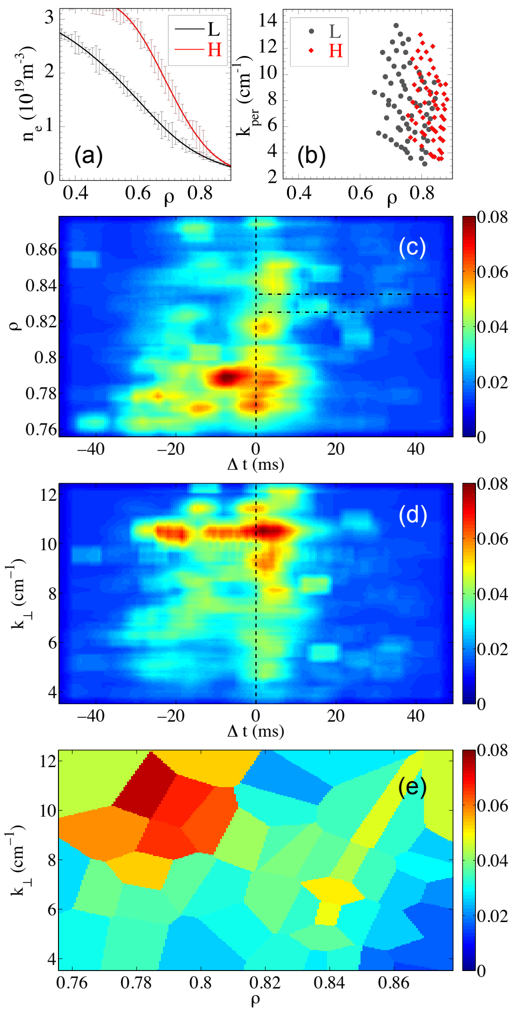

Figure 2: Series of 25 discharges in the configuration with $\iota(a)/2\pi = 1.630$. Total auto-bicoherence of complex Doppler reflectometry data. (a) Density profiles in the L and H phases. (b) Position ρ and $k_\perp$ of the measurement channels in the L and H phases. (c) Mean auto-bicoherence vs. time and ρ. (d) Mean auto-bicoherence vs. time and $k_\perp$. (e) Mean auto-bicoherence vs. ρ and $k_\perp$.

The slow L–I–H transition

Fig. 3 shows the auto-bicoherence for a different series of discharges in the configuration with $\iota(a)/2\pi = 1.553$. The elaboration of this figure is equivalent to that of Fig. 2. The mean line average density at the transition is about 50% lower than with the previous configuration. Another difference with the previous result is that in these discharges, the transition at $\Delta t = 0$ is not into the H-mode, but rather into the intermediate (I) phase between the L-mode ($\Delta t < 0$) and the H-mode (starting much later). We conjecture that this situation is due to a weaker zonal flow, incapable of producing the final transition into the H phase. This would be consistent with the observation of the predator-prey relation between turbulence and flows, associated with wave numbers in the range $k_\perp \simeq 6-12$ cm^{-1}.

Discussion and conclusions

In this work, we report measurements of the bicoherence across the L-H confinement transition at TJ-II [2]. We examine both fast transitions and slow transitions characterized by an intermediate (I) phase. The bicoherence, understood to reflect the non-linear coupling between the perpendicular velocity (zonal flow) and turbulence amplitude, is significantly enhanced in a time window of several tens of ms around the time of the L–H transition. It is found to peak at a specific radial position, slightly inward from the radial electric field shear layer in H mode. In addition, it is associated with a specific perpendicular wave number range ($k_\perp \simeq 6-12$ cm^{-1}), indicating which turbulence scales are the relevant ones in the zonal flow generation at the L-H transition. In all cases, the bicoherence is due to the interaction between high frequencies and a rather low frequency, as expected for a zonal flow, thus conforming the generic transition theories.

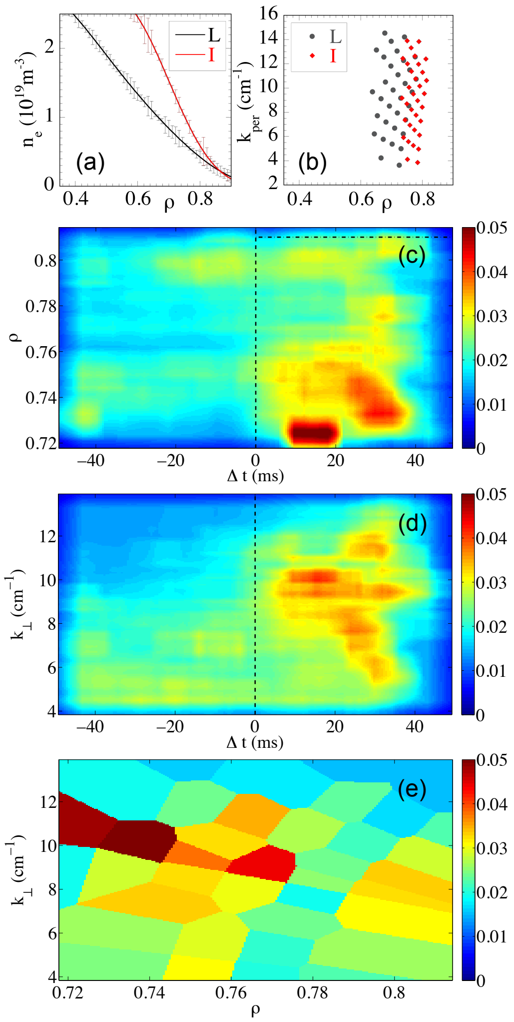

Figure 3: Series of 26 discharges in the configuration with $\iota(a)/2\pi = 1.553$. *Total auto-bicoherence of complex Doppler reflectometry data. (a) Density profiles in the L and I phases. (b) Position* ρ *and* $k_\perp$ *of the measurement channels in the L and I phases. (c) Mean auto-bicoherence vs. time and* ρ. *(d) Mean auto-bicoherence vs. time and* $k_\perp$. *(e) Mean auto-bicoherence vs.* ρ *and* $k_\perp$.

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