Evidence of multi-scale correlations of fluctuations during transition to high confinement regimes in the TJ-II stellarator plasmas

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I.- Introduction

It has been previously shown that long range cross-correlation between potential signals shows a maximum value (about 0.5) when plasma density is close to the threshold for the development of spontaneous edge sheared flows ($n \approx 0.6 \times 10^{19}$ m^{-3} for the magnetic configuration used). Furthermore, correlation increases in plasma regimes with edge biasing induced enhanced confinement. These findings have shown the important role of long distance correlation as a first step in the transition to improved confinement regimes and the key role of electric fields to amplify them [1].

Recent experiments in TJ-II with Li-coating [2] and NBI heating have shown evidence of spontaneous bifurcations with characteristics of plasma transition to improved confinement regimes (H-mode) [3]. Near the plasma conditions where the (L-H) transport bifurcation occurs (characterized by a plasma density of $n \approx 2 \times 10^{19}$ m^{-3}), the correlation rises up to 0.7 - 0.8.

The mechanisms governing the development of this L-H bifurcation, leading to the establishment of a transport barrier, is still one of the main scientific challenge facing the magnetic fusion community, after more than twenty years of intense research since the H-mode discovery [4]. The results presented here show the importance of multi-scale physics as a new experimental fingerprint of the plasma behaviour during transport bifurcations providing a critical test for Low to High (L-H transition) models in fusion plasmas. This is in line with the expectation that multi-scale interactions are a crucial ingredient of complex dynamics in many non-equilibrium systems.

II.- Experimental set-up

Experiments were carried out in the TJ-II stellarator in ECRH / NBI heated plasmas ($P_{ECRH} \leq 400$ kW, $P_{NBI} \leq 400$ kW, $B_T = 1$ T, $\langle R \rangle = 1.5$ m, $\langle a \rangle \leq 0.22$ m, $\iota(a)/2\pi \approx 1.6$) with

Li-coated wall conditions. A full set of plasma diagnostics has been used to characterize plasma profiles and fluctuations. In particular, TJ-II is equipped with a unique system for multi-scale physics studies: two Langmuir probes systems located in two different toroidal positions installed on fast reciprocating drives. One of the probes (Probe 1) is located in a top window entering vertically through one of the "corners" of its beam-shaped plasma and at $\phi \approx 35^o$ (where f is the toroidal angle in the TJ-II reference system). Probe 2 is installed in a bottom window at $\phi \approx 195^o$ and enters into the plasma through a region with a high density of flux surfaces (i.e. lower flux expansion) than Probe 1. This unique experimental set-up allows the simultaneous investigation of short and long-range fluctuation scales in the plasma edge [1].

III.- Transition to improved confinement regime

The new TJ-II experimental set-up with Li-coating wall [2] and NBI heating have shown evidence of spontaneous bifurcations characterized by the increase of plasma density and stored energy with a concomitant reduction in the H_α emission (showing a decrease of the outward particle flux) together with the reduction of the level of broadband fluctuations and a steeper density gradients. All these phenomena are characteristic of plasma bifurcations to improved confinement regimes (H-mode) [3]. Figure 1 shows the time evolution of plasma density, H_α and fluctuation level during ECRH and NBI phases. During this NBI phase spontaneous L-H transition is observed. The H-mode is (so far) obtained in a transient way (during few energy confinement times). Edge fluctuations (rms values) are significantly reduced at the L-H transition (typically a factor of 2 – 3) in a short time scale (few tens of microseconds). This reduction is due to the drastic modification of the frequency

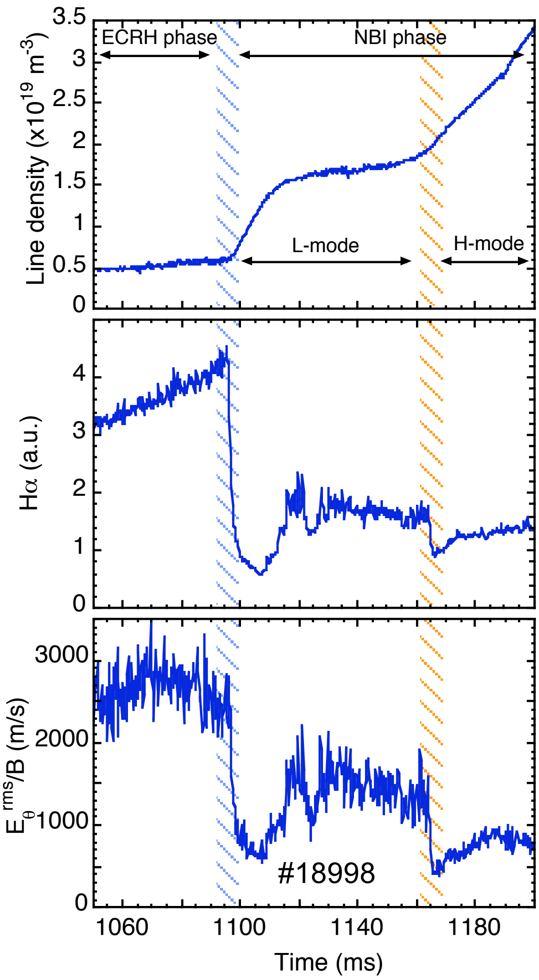

Fig. 1 *Time traces during ECRH and NBI phases. Blue shadow area separates ECRH and NBI regimes Red shadow area shows the L-H transition time. Shot 18998.*

spectra of density and potential fluctuations. However, it is remarkable that whereas density fluctuations are reduced in a wide frequency range (1 – 200 kHz), low frequency fluctuations (below 50 kHz) in potential signals are not affected at the L-H transition.

IV.- Long-distance correlation measurements

In order to quantify the degree of long and short range similarity of density and potential fluctuations we have computed the normalized cross-correlation defined as

$$\gamma_{xy}(\tau) = \frac{E\{[x(t+\tau)-\bar{x}][y(t)-\bar{y}]\}}{\sqrt{E\{[x(t)-\bar{x}]^2\}.E\{[y(t)-\bar{y}]^2\}}}$$

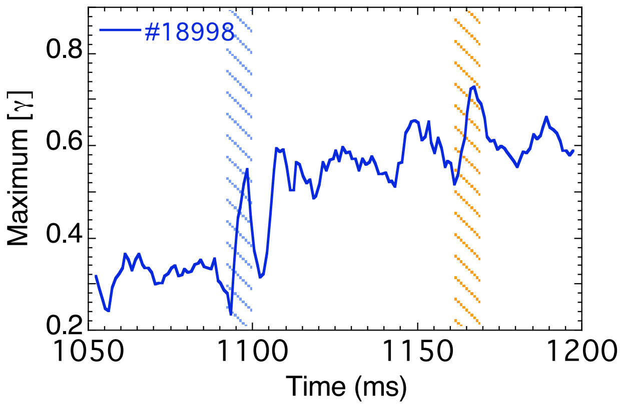

Fig. 2 Time evolution of long-range correlation between potential signals toroidally apart. Blue shadow area separates ECRH and NBI regimes. Red shadow area shows the L-H transition time. Shot 18998.

The degree of long-range coupling for potential fluctuations is significant in the L-mode regime and strongly intermittent. At the bifurcation point (L-H transition) the degree of long-range correlations between current (i.e. density) fluctuations is reduced with a simultaneous increase in the long-range coupling between potential fluctuations (figure 2). The cross-coherence spectrum for potential fluctuations (figure 3) shows the frequency band involved in each regime: in spite of the fluctuations reduction in the transition to the H-mode, cross-coherence increases for the low frequency band remaining (below 50 kHz).

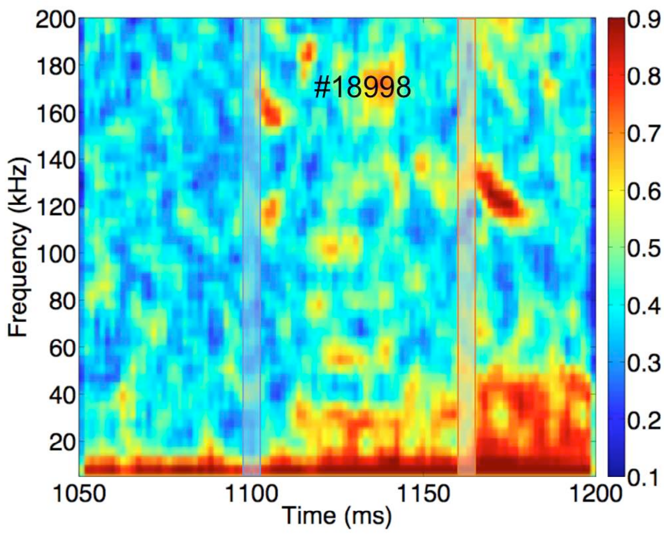

Fig. 3 Long-range correlation spectrum (potential signals). Blue shadow area separates ECRH and NBI regimes. Red shadow area shows the L-H transition time. Shot 18998.

V.- Discussion and conclusions

Multi-scale mechanisms are a finger-print of L-H transition models based on the influence of flows driven by turbulence in which local fluctuations (short scales) can provide via non-local inverse cascades large scale structures. The detection of long-range correlation in stellarators [5, 6] and tokamaks [7] is consistent with the theoretically predicted zonal flows (low frequency structures) [8]. In the framework of L-H transition models based on secon d / first order phase transitions, fluctuations are expected to show long range correlations in the order parameter related with the electric fields (i.e. plasma potential) which would be amplified by symmetry breaking mechanisms (i.e. via electric fields). Then, TJ-II findings are fully consistent with this theoretical framework.

In the framework of L-H transition there exist other models, like those based on particle orbit losses or Stringer spin-up [9], that might also give rise to localized perturbation in the plasma potential which parallel propagation could also trigger long range correlations in potential fluctuations; however, in this case, it remains to be clarified why such particle orbit losses induced long-range correlations should be amplified by electric fields, because radial electric fields are expected to reduce both edge particle losses and the degree of poloidal asymmetries during transition to improved confinement regimes [10]. Comparative studies in different magnetic confinement devices on multi-scale physics and input from large-scale simulations would be particularly interesting to unravel the underlying physics of long-range correlations during the development of transport barriers.

The presented experimental findings clearly show the importance of multi-scale physics mechanisms (long-range spatial correlations) as a new experimental fingerprint of the plasma behaviour during transport bifurcations in fusion plasmas providing a critical test for Low to High (L-H transition) models.

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