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

T. Estrada¹, T. Happel², C. Hidalgo¹, E. Ascasíbar¹, E. Blanco¹ and the TJ-II Team¹

¹ Laboratorio Nacional de Fusion, As. Euratom-CIEMAT, Madrid, Sapin
² MPI fur Plasmaphysik, As. Euratom-IPP, Garching, Germany

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, $E_r$, and $E_r$-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 $⟨n_e⟩ = 2 - 4 \times 10^{19}$ 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 $H_{\alpha}$ 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 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 $\rho - \rho_{\text{shear}} = +0.01, -0.01, -0.03, -0.06$ and -0.07). The vertical line indicates the H-L back transition.

Figure 1: (a): The time evolution of plasma density, energy and $H_{\alpha}$ (b) $E_r$ and (c) $\bar{n}_e$ measured, from top to bottom, at $\rho - \rho_{\text{shear}} = +0.01, -0.01, -0.03, -0.06$ and -0.07. The vertical line indicates the H-L back transition.
The evolution of the turbulence reduction profile (figure 2.b) clearly shows the distinctive behaviour of the density turbulence at both sides of the $E_r$-shear layer location. At each radial position, 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 increase in the turbulence level is measured at the inner radial positions, no change in the turbulence 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 $E_r$ declines and produces a gradual increase in the turbulence level at the innermost radial positions, reaching the $E_r$-shear location right before the H-L back-transition. The consequence is a gradual retreat of the transport barrier quantified 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 fluctuation 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 turbulence. 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 relationship: a periodic behaviour with $E_r$ (predator) following the density fluctuation level (prey) with
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 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 $\bar{n}_e$ 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