L-H transition experiments in TJ-II

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Abstract

In the TJ-II stellarator, L- to H-mode transitions are achieved under NBI heating conditions when operating under lithium coated walls. Several magnetic configurations have been explored in order to study the influence of the rotational transform in the transition. The shear of the negative radial electric field, E_r, increases at the L-H transition by an amount that depends on the magnetic configuration and heating power. Magnetic configurations with and without a low order rational surface close to the plasma edge show differences that may be interpreted in terms of local changes in the radial electric field induced by the rational surface that could facilitate the L-H transition. Fluctuation measurements show a reduction in the turbulence level that is strongest at the position of maximum E_r shear. High temporal and spatial resolution measurements indicate that turbulence reduction precedes the increase in the mean sheared flow, but is simultaneous with the increase in the low frequency oscillating sheared flow. These observations may be interpreted in terms of turbulence suppression by oscillating flows, the so-called zonal flows.

1. Introduction

Turbulence de-correlation by sheared flows was proposed in 1990 [1] and confirmed experimentally in the DIII-D tokamak [2], as the mechanism that leads to a strong reduction in turbulence and the formation of transport barriers. At present most experimental evidences support this paradigm to explain the H-mode reduced transport, although the underlying mechanism that generates the electric fields is still an open issue. More recently, the relevance of zonal flows on turbulence regulation and formation of transport barriers has been identified [3,4].

The H-mode develops in both tokamaks and stellarators across a wide plasma parameter range [5]. Helical devices provide valuable contributions to H-mode physics due to their distinctive characteristics, *i.e.* low/high magnetic shear, magnetic field ripple, neoclassical ambipolar electric field [6]. In particular, some specific characteristics of the stellarator TJ-II, *i.e.* low magnetic shear and high magnetic configuration flexibility, allow controlling the position of low order rational values within the rotational transform profile and, therefore, the study of how the magnetic topology affects the L-H transition. In TJ-II, L-H transitions have been achieved in NBI heated plasmas [7], when operating under lithium coated walls [8]. First L-H transition studies in TJ-II have shown a dependence of the H-mode "quality" on the rotational transform [9]. In this work dedicated fine rotational transform scans are reported.

2. Experimental set-up

TJ-II is a helical device with major radius R = 1.5 m, minor radius <a> ≤ 0.22 m and magnetic field $B_0 < 1.2$ T. TJ-II offers the possibility to explore a wide rotational transform range in low, negative magnetic shear configurations. Plasmas are started up and heated by ECH 2nd harmonic using two gyrotrons at 53.2 GHz with X-mode polarization. The maximum power per gyrotron is 300 kW and the power density is about 10 W/cm^3 [10]. Under these heating conditions the plasma density has to be kept below the cut-off value of 1.75 10^{19} m^{-3}. Higher density plasmas are achieved using NBI heating. Two injectors, one *co-* and one *counter-*, are in operation delivering a port-through power per injector up to 500 kW. The experimental results presented below were obtained in hydrogen plasmas.

A two-channel Doppler reflectometer [11], recently installed in TJ-II, is used to experimentally investigate radial electric fields and turbulence dynamics. As it has been shown in the W7-AS stellarator, this diagnostic technique allows the measurement of the perpendicular rotation velocity and density fluctuations on various scales with good spatial and temporal resolution [12]. Besides, measurements made simultaneously at two different radial positions, as those carried out in the ASDEX Upgrade tokamak [13], allow information on the temporal evolution of the radial electric field and its shear to be obtained.

3. H mode studies

3.1 Magnetic configuration scan

H-mode transitions are achieved under NBI heating conditions when operating with lithium coated walls [8]. H-mode transitions reproduce common features found in other devices [5]: i.e. 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. They are observed at moderate input powers, with one (co-injector) and with two (co- and counter-) NBIs (about 400 kW port through, each).

Previous L-H transition studies in TJ-II have shown a dependence of the H-mode “quality” on the rotational transform [9]. Several different magnetic configurations were explored, predominantly two with edge rotational transform values close to 1.6 (n/m=8/5) in plasmas heated with one NBI (co-injector). This study has revealed some differences when comparing the transition characteristics in the two magnetic configurations. In the $\iota(a)$=1.63 configuration, increments of up to 30% in the confinement enhancement factor (defined as the ratio between the experimental energy confinement time and that given by the ISS04 [14], $H_{ISS04}= \tau_E/ \tau_{ISS04}$) are measured while maximum values of 20% are obtained in the $\iota(a)$=1.59 configuration. Edge density profiles measured by AM reflectometry [15] show an increase in the density gradient more pronounced in the $\iota(a)$=1.63 configuration; at $\rho \approx 0.8$ the density gradient increases from about 2 to 6x10^{20} m^{-4} within 2-4 ms after the L-H transition, whereas it only increases up to 4x10^{20} m^{-4} in the $\iota(a)$=1.59 configuration. Transport analysis has been done with the ASTRA system [16] using the experimental profiles of radiated power, plasma density, and electron and ion temperatures. Changes in the energy confinement time from about 7 to 8 ms are obtained, in agreement with those obtained experimentally. Particle confinement times close to 55 ms are obtained increasing by 25% and 35% in the magnetic configurations with $\iota(a)$=1.59 and $\iota(a)$=1.63, respectively.

Finally, an E_r field-well of about 12 kV/m is measured at effective radius ρ ≈ 0.8 in the ι(a)=1.63 configuration whereas it remains below 9 kV/m in the ι(a)=1.59 configuration. The differences found when comparing these configurations suggest a possible role of the 8/5 rational on the transition [9].

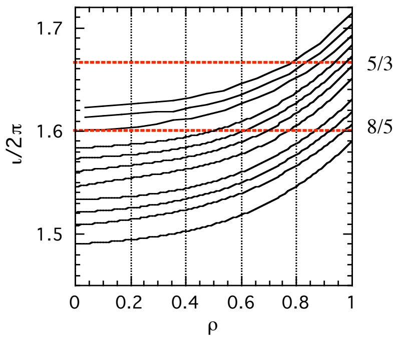

Figure 1: Vacuum rotational transform profiles

In order to proceed with these studies, a fine rotational transform scan has been carried out covering vacuum ι/2π values at ρ=1 between 1.59 and 1.71. The rotational transform profiles are shown in figure 1. To estimate the "quality" of the H-mode, both, the relative increase in the confinement enhancement factor over the L-mode value and the absolute value of the radial electric field well, have been selected and are shown in figure 2.a and 2.b as a function of the edge rotational transform. Both magnitudes show similar iota-dependences. The NBI absorbed power normalized to that given by the H-mode power threshold scaling [17] is shown in figure 2.c. The change in the NBI absorbed power is mainly due to the dependence of the NBI absorbed power on the plasma density (estimated using the FAFNER2 code that takes into account shine through, CX and ion losses) and to a lesser extent to the input power that lies between 370 and 400 kW in these discharges. The dependence found in this fine magnetic configuration scan suggests a positive influence of low order rationals close to the plasma edge (ρ≈0.8), supporting previous observations [9]. Moreover, the magnetic configurations with the rational 5/3 close to the plasma edge show that the L-H transition requires a certain plasma current that depends on the magnetic configuration. Figure 3 shows the vacuum rotational transform profiles, the plasma current at which the L-H transition takes place and the radial electric field profiles measured in L and H modes at three magnetic configurations having the rational 5/3 close to the plasma edge. As the vacuum rotational transform decreases, the plasma current required to trigger the transition increases which indicates a preferential radial position for the rational to ease the transition.

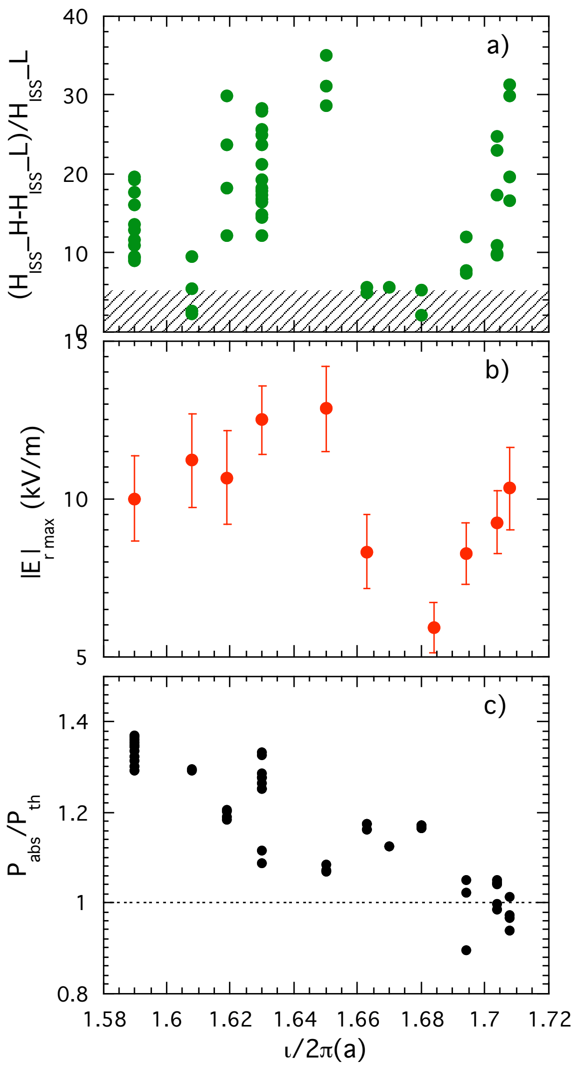

Figure 2: Increase of the H factor over the L-mode value (a), absolute value of E_r field-well measured at ρ=0.75-0.8 (b) and NBI absorbed power normalized to that given by the H-mode power threshold scaling (c), as a function of iota.

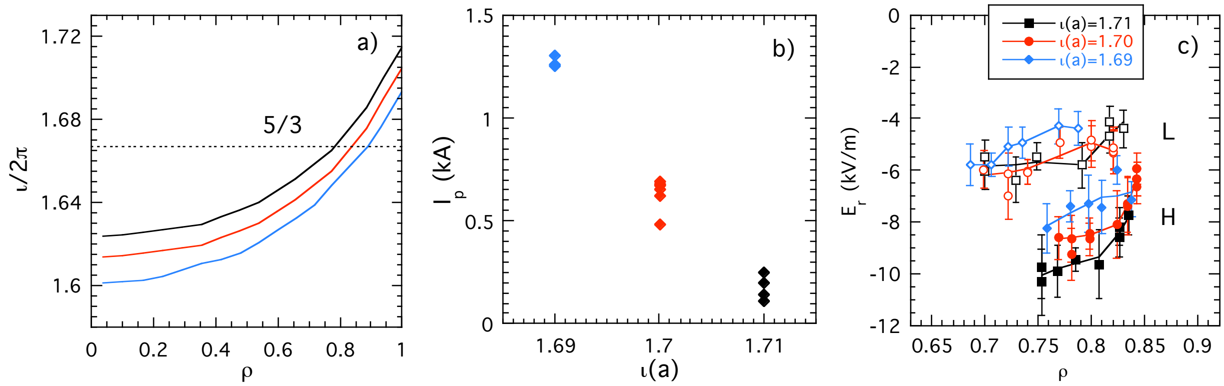

Figure 3: Vacuum rotational transform profiles (a), plasma current at which the L-H transition takes place (b) and radial electric field profiles in L- and H-mode at three magnetic configurations (c).

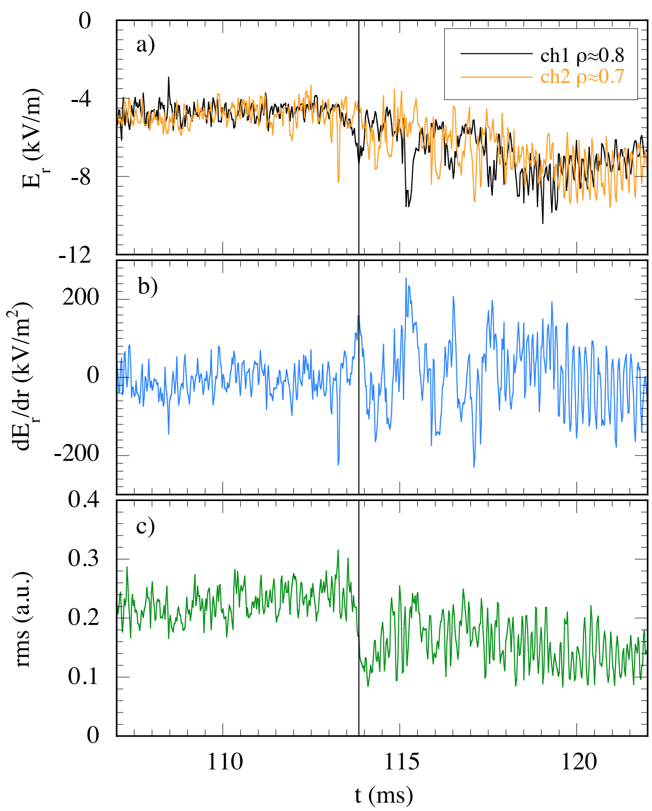

Figure 4: Time evolution of E_r at two radial positions (a), E_r field shear (b), and density fluctuations (c), in a magnetic configuration with the rational 5/3 close to ρ = 0.8. The vertical line indicates the L-H transition time

In these configurations, pronounced oscillations in radial electric field are detected at the transition that are absent in configurations without low order rationals. These oscillations represent local changes in the E_r field which may be induced by the rational surface facilitating the transition and giving rise to steeper density gradients, a higher confinement enhancement factor and a deeper electric field well. An example obtained in the ι(a)=1.7 magnetic configuration (5/3 close to ρ = 0.8) is shown in figure 4. The figure shows the time evolution of the radial electric field at two adjacent radial positions (figure 4.a), the radial electric field shear (figure 4.b) and the density fluctuation level (figure 4.c). The L-H transition time is indicated in the figure by a vertical line. Fast and marked changes in the radial electric field are detected in the outer channel (ρ≈0.8 in figure 4.a) giving rise to pronounced changes in the radial electric filed shear (figure 4.b); these changes start right at the transition where a reduction in the fluctuation level is detected (figure 4.c). This result can be interpreted in terms of local changes in the radial electric field shear induced by the 5/3 rational surface which may facilitate or even trigger the transition.

As it has been pointed out, these experiments have been carried out at relative low NBI input power. Under these conditions, a reduction in the "effective" power threshold due to the rational surface could explain the pronounced iota-dependence found in this magnetic configuration scan.

So far, only a few configurations have been explored heating the plasmas by both injectors -see next section-, thus, further experiments are planned to study the iota dependence of the L-H transition at powers well above the threshold level.

3.2 High NBI input power

In plasmas heated by both NBIs (with ≈900 kW port-through), an E_r field-well of about 15 kV/m is measured at ρ: 0.8-0.85, about 3 cm inside the last closed flux surface. The position of the maximum shear in the perpendicular velocity is close to ρ = 0.85 and it is at this position where the maximum increase in the density gradient and the strongest reduction in the turbulence take place. Figure 5.a shows the radial profiles of the perpendicular rotation velocity in L and H mode in a plasma heated with both NBIs in the standard magnetic configuration with ι(a)=1.65. The fluctuation level shows a factor five reduction at the location of the maximum velocity shear. The ratio between the density fluctuations during the H and L modes is shown in figure 5.b.

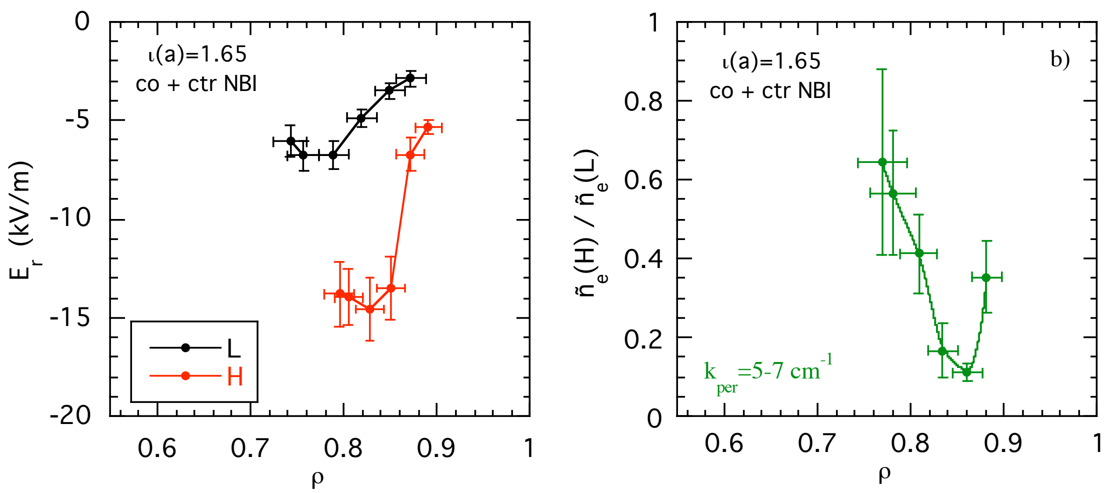

Figure 5: Radial profiles of E_r in L and H modes (a) and density fluctuation reduction (b), in plasmas heated by both NBIs (total 900 kW port-through) in the ι(a)=1.65 configuration

A closer look at the time evolution of both, the radial electric field shear and the density fluctuations, indicates that the reduction in density fluctuations precedes the increase in E_r field shear. This result resembles that recently found in JET [18] and seems to be in contradiction with numerous experimental observations supporting the paradigm of sheared electric field suppression of turbulence as unique element to explain transitions to improved confinement regimes [2, 19]. A detailed analysis of the signals reveals an increase in the fluctuations of the E_r field and E_r field shear within the frequency range 1-10 kHz just at the transition. The increase in the low frequency E_r fluctuations and the reduction in the high frequency density fluctuations are measured a few ms before the E_r field shear development. Figure 6.a shows the time evolution of the E_r field at two adjacent radial positions; the difference between the E_r field at these two radial positions and the high frequency density fluctuations are shown in figure 6.b; finally, the evolution of the low frequency fluctuations in the E_r shear is shown in figure 6.c. The L-H transition time is indicated in the figure by a vertical line. This example indicates that the turbulence reduction precedes the increase in the mean sheared flow, but it is simultaneous with the increase in the low frequency oscillating sheared flow. This observation may be an indicator, albeit insufficient, of the existence of zonal flows. As it is explained in Refs. [3, 4], additional

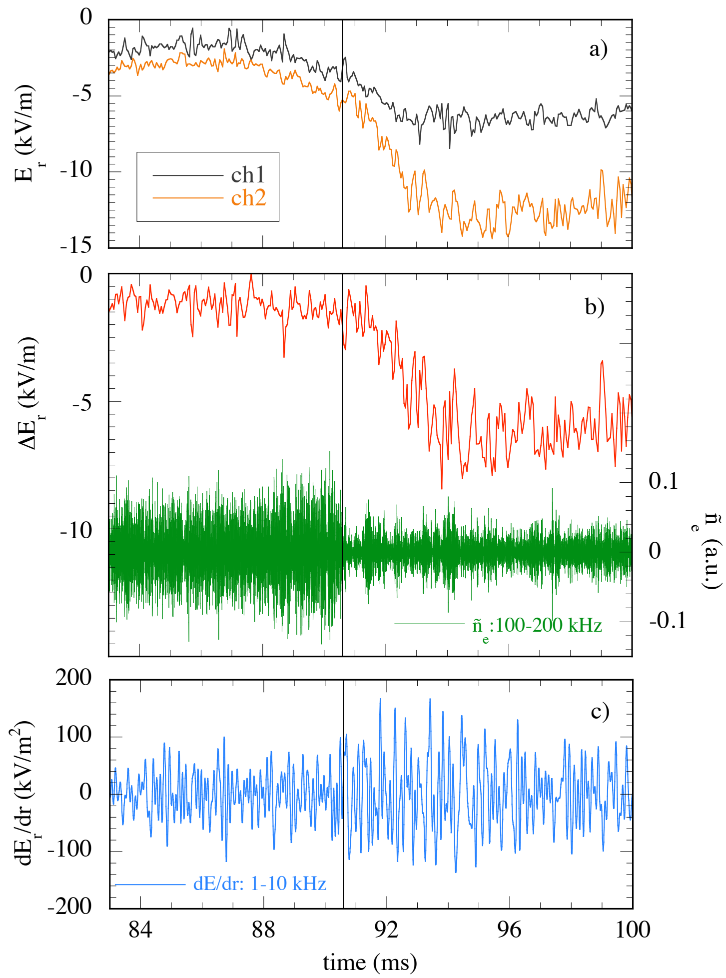

Figure 6: Time evolution of E_r at two adjacent radial positions (a), their difference and the high frequency density fluctuations (b) and the low frequency fluctuations in E_r shear (c); plasma heated by both NBIs (900 kW port-through) in the configuration ι(a)=1.65. The vertical line indicates the L-H transition time.

three-dimensional measurements are required to asses the toroidal and poloidal symmetry of the oscillating sheared flows and their finite radial wavelength. In TJ-II, the degree of long range similarity of density and potential fluctuations has been measured using the two Langmuir probes sets. Long-range correlations in the plasma potential reach values of up to 0.7-0.8 at the L-H transition whereas density fluctuation are always dominated by short range scales [20]. These results are consistent with L-H transition models predicting plasma bifurcations triggered by zonal flows [21].

Conclusions

L-H transitions are observed in NBI plasmas when operating under Li-coated walls:

A fine magnetic configuration scan performed at low NBI input power (≈ 400 kW) shows a dependence on the rotational transform of both, the increase in the confinement enhancement factor and the radial electric field well. The dependence found in this fine magnetic configuration scan suggests a positive influence of low order rationals (8/5 and 5/3) when located close to the plasma edge (ρ≈0.8). The observations may be interpreted in terms of local changes in the radial electric field induced by the rational surface that could facilitate or even trigger the L-H transition.

Higher NBI input power (≈ 900 kW) experiments have been performed in the standard magnetic configuration. Fluctuation measurements show a reduction in the turbulence level that is most pronounced at the position of maximum E_r shear. High temporal and spatial resolution measurements indicate that turbulence reduction precedes the increase in the mean shear flow, but is simultaneous with the increase in the low frequency oscillating shear flow. These observations are consistent with L-H transition models predicting plasma bifurcations triggered by zonal flows.

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