Overview of TJ-II experiments

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Abstract. This paper presents the last results on confinement studies in the TJ-II stellarator. The research of the dependence of spatially resolved transport coefficients on plasma parameters for ECH plasmas with Boronised wall shows that the heat confinement increases linearly with density while particle confinement increases sharply a factor four above a certain density threshold associated with the positive electric field. Remarkably, lowest order magnetic resonances, even in a low shear environment, reduce locally the effective diffusivities. The inherently strong plasma wall interaction of TJ-II has been successfully reduced after Lithium coating by vacuum evaporation. Besides H-retention and low Z, Li was chosen because there exists a reactor-oriented interest in this element, thus giving especial interest to the investigation of its properties. The Li-coating has led to important changes in plasma performance. Particularly, the effective density limit in NBI plasmas has been extended reaching central values of 8 x 10^{19} m^{-3} and Te≈250-300 eV, with peaked density, rather flat Te profiles and increased ion temperatures. Alfvén modes are destabilised and their influence on fast ion confinement is studied in NBI discharges. Due to the achieved density control, a second type of transitions has been added to the low density ones previously observed in boronised wall. The high density transitions, under NBI with Li-coated walls are characterised by the fall of Hα emission, the onset of steep density gradient, and the reduction of the turbulence, which are characteristics of transition to H mode. TJ-II is therefore a unique device where first and second order phase transitions can be investigated.

1.- Introduction.

TJ-II is a stellarator of the heliac type, characterised by its high flexibility and its almost flat rotational transform profile [1]. TJ-II is provided with a central conductor composed of two coils: a helical and a circular one. By changing the currents that circulate by these coils, it is possible to modify the plasma shape as well as the rotational transform. The central conductor is protected by a groove that acts as helical limiter, defining the last closed magnetic flux surface (LCFS). The plasma wall interaction is therefore maximum at the groove, which can be very close to the magnetic axis (about 12 – 14 cm, depending on the configuration), thus provoking a strong recycling and impurity influx. Several strategies to solve this problem have been essayed, but the last and most successful one has been coating the TJ-II with Li. So, in the present work, the operation of a stellarator, the TJ-II Heliac, with lithium-coated walls is described for the first time. The Li-coating implies an important reduction of sputtering and recycling. The most relevant changes on the plasma performance and confinement characteristics associated to the new wall scenario are described and analysed in terms of enhanced impurity and particle control.

Beyond the specific TJ-II achievements, the research on Li-coated wall properties is an outstanding topic itself, since plasma wall interaction issues are paramount in achieving fusion plasmas with high purity, controlled density and high confinement. The interaction with the first wall, reached by charge exchange (CX) neutrals, photons and some more or less tenuous plasma, is considered to contribute to the plasma impurity content as much as the wetted areas do. Stellarator plasmas show distinct features in their interaction with the surrounding materials in comparison to tokamaks. Stellarators do not present disruptions, type I ELMs or MHD-driven density limit [2], which make them more reliable for reactor operation. However they present a significantly higher aspect ratio thus offering a less favourable area to volume ratio. Several specific divertor concepts have been developed for stellarator with reasonable success for impurity and particle control [3], but no specific coating strategies for the first wall exist. The divertor concepts are based on the natural topology of the configuration, using the magnetic islands that appear in the edge. For these divertors to be successful it is necessary that the magnetic topology does not change during the plasma operation, so a new concept must be developed for stellarators with varying magnetic topology: The flux expansion divertor [4] has not been explored experimentally up to now but theoretical studies are underway in TJ-II [5].

Compared to other low Z coating elements such as Be, C and B, lithium is a very attractive element due to its very low radiation power, strong H retention and strong O getter activity and excellent results have been achieved recently in tokamaks [6], with positive impact on energy confinement [7], as has been previously predicted [8]. Moreover, the research on Li properties has strong interest regarding the liquid lithium based divertors that are envisaged for future reactors.

This paper presents an overview of experimental results in the new TJ-II conditions. Remarkably, a new regime for TJ-II operation, with stationary NBI discharges where n_e and τ_E double and radiative losses drop has been achieved by drastically reducing wall recycling by Lithium coating. The transitions to such regime are described below showing the properties of those plasmas. After reaching such transitions, TJ-II appears as a unique experiment, since both types of phase transitions have been observed in this device. The relationship between electric fields, turbulence and transport has been established during spontaneous or provoked transitions to improved confinement regimes.

The reminder of this paper is organised as follows. Section 2 is devoted to the presentation of Li coating techniques and the properties of the plasma in these new conditions. The observed transitions and their properties are shown in Section 3. Finally, summary and discussion of the results presented here come in Section 4.

2.- Plasma confinement with Li-coated walls.

The design of the TJ-II vacuum chamber imposes specific plasma-wall interaction issues that have strong influence on confinement: The helical limiter, where most of recycling and impurity release happens, is physically close to the centre of the plasma, therefore the plasma-wall interaction control is a key element in TJ-II operation. The effect of Li-coating walls on plasma performance can be ascribed to the associated changes in recycling, radiated power and impurity penetration, all of them having direct impact in the particle and energy confinement. In the previous experimental campaigns, the experience with TJ-II plasmas came from ECH (normally with line densities in the range 0.4 to $0.9 \cdot 10^{19}$ m^{-3}) and NBI discharges in boronized wall.

In the last experimental campaign, the TJ-II stellarator has been coated with Lithium by vacuum evaporation [9]. The technique used for lithiumization is the evaporation by ovens and the Li is homogenised in the vessel walls by the plasma itself that is seen to distribute the Li. The choice of Lithium was mainly motivated by its high efficiency for H retention and low Z and by the interest in this element, in particular for liquid divertor concepts. Lithium coating has led to important changes in plasma performance. Particularly conspicuous has been the strong decrease in recycling associated to the new wall conditions, but also in impurity content, with direct impact on radiative losses and total energy confinement, as expected in a first-wall dominated plasma-wall interaction device. The O gettering is still maintained by the boron layer that is deposited under the Li one. The edge radiation is observed to fall, which avoids the power unbalance that produces the low radiation collapse. Changes in the shot by shot fuelling characteristics as well as in the total particle inventory compatible with good density control and plasma reproducibility under ECRH scenarios have been recorded after the Li deposition. Thus, a rise by a factor 2 to 3 in the fuelling rate at constant density compared with the B-coated walls is recorded, and even a higher factor is estimated for the allowed H inventory at the walls. These changes are mirrored in the radiation and edge radial profiles, mostly ascribed to the replacement of dominant impurity at the edge: the Li-cooling rate properties are much more favourable than the ones of the usual impurities in TJ-II. The new wall conditions lead to the extension of the effective density limit in NBI heating scenarios and to stationary NBI plasmas above ECH cutoff densities. Transport studies on these plasmas show much better general confinement properties. Central electron densities up to 8 x 10^{19} m^{-3} with electron temperatures of 250-300 eV have been recorded, with peaked density and rather flat Te profiles.

Even though total radiation could account for half of the injected power in some instances, the development of a radiative instability at the edge, which seems to be closely linked to the density limit in current-free devices, has not been observed. This is in line with the peculiarities of the cooling rate for Li atoms in the range of edge temperatures prevailing in the new scenario.

Beyond Lithium coating, the flux expansion divertor concept is being explored as a possible future strategy to diminish the plasma-wall interaction in TJ-II plasmas [5]. The 3D structure of the ion collisional flux onto the vacuum chamber is obtained by means of the code ISDEP [10] showing that the groove is the preferred zone for the escaping particles to strike. We have found several magnetic configurations that are suitable for the flux expansion divertor concept, since they have plasma zones where the density of magnetic surfaces is especially low, i. e., where the flux expansion is large enough, and strategies for intersecting the particle and heat flux are under study.

One of the main advantages of Li-coated walls, compared to former boronized walls, is the strong improvement of control of plasma density by external puffing: The required puffing levels were significantly higher, by a factor of 2-3, for the same density, moreover, no sign of saturation was observed after a full day of ECRH operation. Particle balance yields a retention of H under the Li coated walls a factor 4 higher than the B wall saturation limit. The dynamic behaviour of plasma particles during perturbative experiments shows that the effective fuelling is close to unity and the recycling coefficient R<0.20.

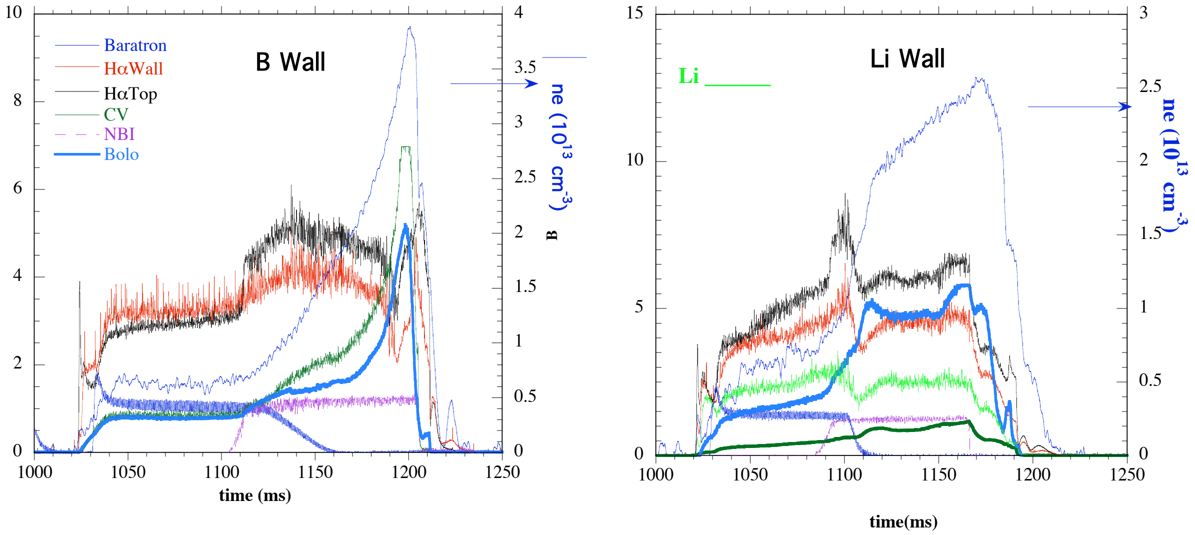

Figure 1: Time evolution of some characteristic parameters (line density, Hα emission from two monitors, C V emission, NBI signal, radiated power, and baratron, i. e., puffed gas pressure) for two representative examples of B (left) and Li (right) walls.

As a result of these facts, density control in NBI plasmas has dramatically improved by the lithium coating. As an example, Figure 1 shows the time evolution of some characteristic parameters for two representative examples of B and Li walls. In both cases ECH power is kept on along the full discharge. As seen, an uncontrolled rise of electron density upon the NB injection takes place in the B case, leading to a plasma collapse. For the Li example, however, a higher density can be achieved, with larger, stationary values of diamagnetic energy content, even when the high level of radiated power represents a larger sink of the available heating power in this case. The density control by external puffing in NBI plasmas is exemplified in Figure 2, where the evolution of the plasma density during NBI injection for three consecutive discharges is displayed: no sign of collapse was seen up to central density values of 8 x 10^{19} m^{-3}, depending on the shape of the resulting plasma profile (see below). A key result is that particle flux to the wall during the NBI phase, as monitored by the Hα detectors located all over the machine, remain at the ECRH plasma level thus implying a strong enhancement (up to a factor of 4) of global particle confinement. This effect is also seen in the Li emission signal and in the particle fluxes deduced from Langmuir probe measurements.

NBI discharges present the appearance of Alfvén Eigenmodes (AE) of frequencies on the order of hundreds of kHz, detected by Mirnov coils as well as HIBP. The influence of AEs on fast ions confinement is studied by using a FILD (Fast Ion Luminiscent Detector) that measures fast ion flux together with their pitch angle and energy [11]. Hα and FILD measurements show that AEs have influence on fast ion confinement when Alfvén mode is located at outer radial positions $\rho>0.6$. Low order rationals are found as key ingredients for AE destabilization and their influence on fast ion confinement [12].

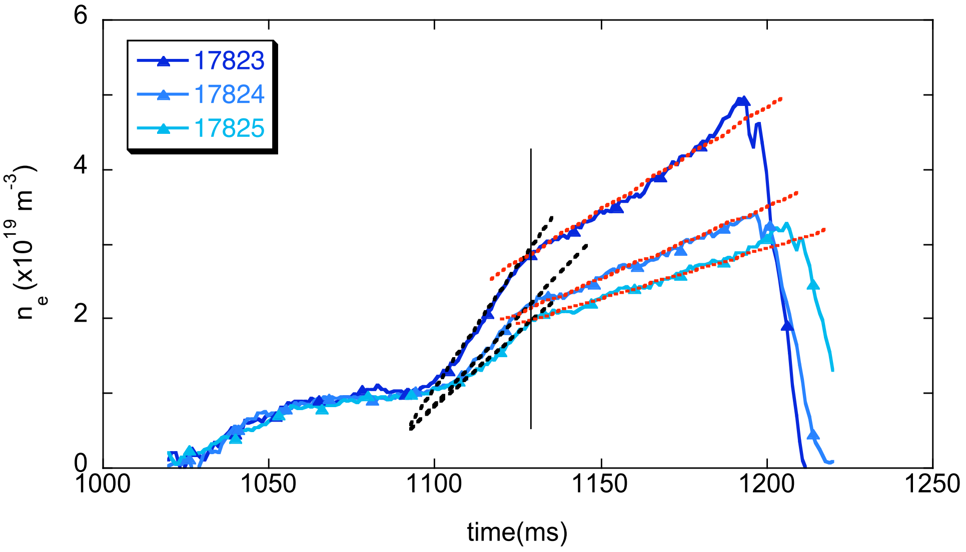

Figure 2: The evolution of the plasma line average density during NBI injection for three consecutive discharges is displayed, showing the achieved density control in NBI plasmas.

Clean plasmas are routinely obtained in TJ-II ECR heated plasmas under low Z scenarios, largely due to the strong oxygen gettering effect of the B coatings and the use of graphite limiters [13]. Although the Li coatings were not aimed at improving this situation, a significant effect has been observed: the density-normalized signals from carbon emission, radiated power, neutral lithium and other impurity-related signals were seen to decrease during the operation day, accompanied by a concomitant evolution of particle recycling towards lower levels. A gradual improvement of the coating homogeneity by plasma erosion of the initial deposition spot can be responsible for the observed behaviour.

As a consequence of the impurity composition and good particle confinement, total radiation levels can be higher in the Li scenarios as compared to those obtained in boronized walls. However, the development of the plasma collapse follows a different pattern in both cases. Higher densities were systematically obtained at the maximum of the W_{dia} signal under Li wall operation, as can be seen in the examples given in Figure 3. Two different radiation profiles were found depending on fuelling strategy and local plasma parameters, shown in Figure 4. For the broad, dome-type profile, central radiation levels are almost half than those observed in the peaked, bell-type counterpart. In spite of their lower total radiated power, development of the dome-type profile was systematically associated to a prompt plasma collapse. This fact can be found in the local power balance established at the plasma edge under central heating conditions. Indeed, the data shown in Figure 4 indicate a significantly lower radiated power at the edge for the peaked, non-collapsing profiles. This balance has been called into play in defining the density limit in stellarators through the so-called *"low-radiative collapse"* [14]. However, with the limited information presently available, other transport-based proposed mechanism for the density limit in stellarators cannot be ruled-out.

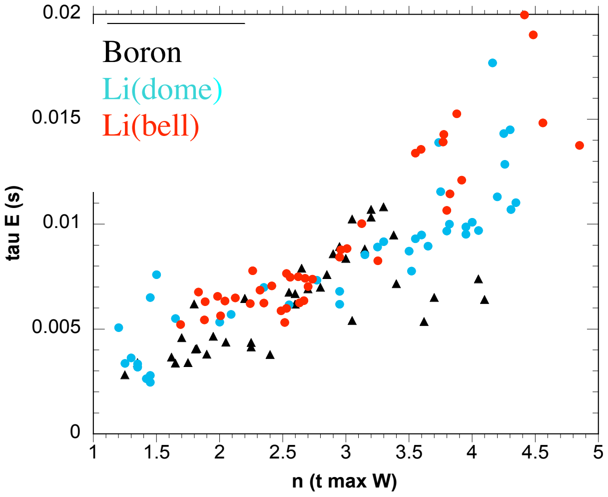

Figure 3: Energy confinement time versus line density for B and Li coated wall discharges.

For the high density, NBI plasmas, ion temperatures up to 150 eV, almost a factor two higher than the characteristic values achieved in ECRH plasmas, were recorded. This is to be compared with the 200-300 eV values for Te simultaneously obtained. Therefore an important share of the available plasma energy takes place between the two main species.

Global energy confinement times were obtained from the diamagnetic loop diagnostic, getting information of the total NBI power from calorimetry measurements, corrected by shine-through an ion losses effects, estimated with the code FAFNER2. The total radiated powers were determined from absolutely calibrated bolometer arrays located at several toroidal and poloidal locations. It is seen that the range of available data extends to larger densities in the Li wall cases as compared to the boron ones, which is a direct consequence of the lower threshold for plasma collapse existing in the later case. In Figure 3, the evolution of energy confinement time (radiation corrected) with average density for different wall scenarios and plasma profiles is shown. It is also seen in the figure that confinement time improves from the boron wall to the Li scenario, the bell-type radiation profiles yielding record values for TJ-II. Second, a supra-linear scaling of τ_E vs. <ne> is observed from the Li-wall scenarios. This enhancement of energy confinement with density is beyond that expected from conventional scaling laws for stellarators [15]. The deduced values of neutral concentration in the region of flat Ti profiles ($\rho = 0 - 0.75$) are in the range of $1\text{-}4.10^{15}$ m^{-3} increasing with plasma density, in good agreement with the predictions of the EIRENE code for TJ-II plasmas, and imply a rather strong channel for ion energy dissipation, with losses in the order of the bolometer values before reported.

3.- Transitions in ECRH and NBI plasmas.

Recent experiments carried out in EC heated plasmas have provided new insights in the underlying physics of sheared flows, with the study of long range toroidal correlations. In addition, NBI sustained plasmas (with Li-coating) have shown for the first time in TJ-II transitions characterized mainly by a reduction in both Hα and broad-band fluctuation level.

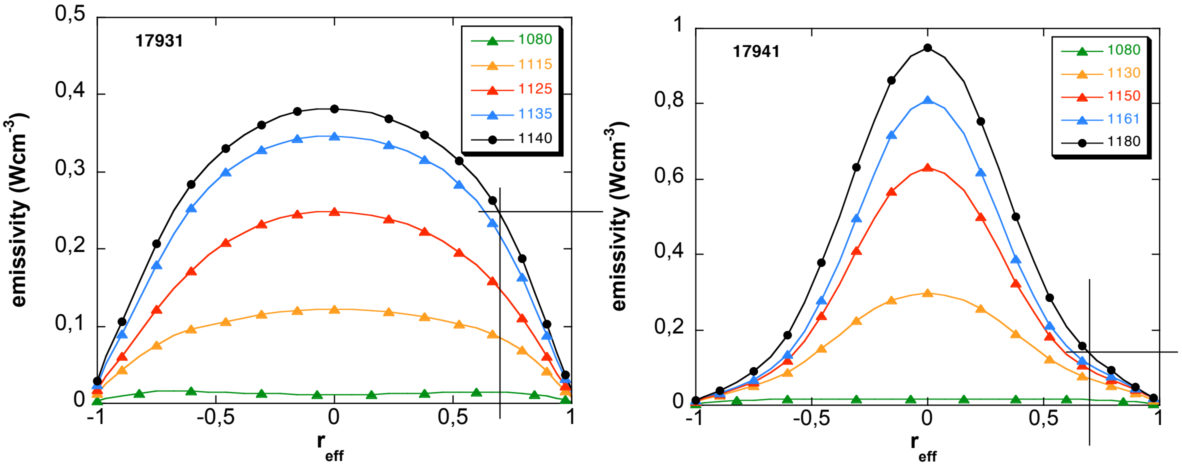

Figure 4: Two different radiation profiles, dome (left) and bell (right) type, were found depending on fuelling strategy and local plasma parameters.

3.1 Transitions in ECRH plasmas

Important ingredients to understand plasma confinement are electric field, dynamics of plasma rotation and turbulence. The inversion of the perpendicular rotation velocity of the turbulence from ion to electron diamagnetic direction [16] is directly connected to an inversion in the radial electric field and the development of the edge shear flows. It can be measured inside the plasma by reflectometry techniques [17] and by Langmuir probes in the plasma edge. It has been shown experimentally that edge perpendicular plasma velocity of TJ-II reverses spontaneously when the line averaged density reaches a certain threshold density in ECRH plasmas (see [18] and references therein). Analysis of local plasma parameters points to plasma collisionality as the magnitude that controls the inversion [19]. For constant temperature, there exists a density threshold to trigger such inversion. Above the threshold density, the turbulent structures (blobs) are stretched and ordered, the confinement improves and fluctuations and sheared flows are self-organized near marginal stability. TJ-II transitions have also been induced using an electrode that externally imposes a radial electric field at the plasma edge [20, 21].

The effective electron thermal, χ_e, and particle, D, transport coefficients with spatial resolution have been studied using ASTRA code [22, 23]. The energy confinement time τ_E increases linearly with density while the particle confinement time steps from low values $\tau_p \sim \tau_E$ to three or four-fold values when crossing the density threshold. This threshold is related to the change of the electric field due to the unbalance of ion and electron fluxes related to kinetic effects. Within the main confining region, χ_e and D decrease with average density. The lowest values for χ_e are found in regions around the positions of lowest order magnetic resonances, showing the influence of magnetic topology on confinement and discovering the evidence of correlation between local values of χ_e and rotational transform. Remarkably, this happens in a low shear, although high rotational transform, environment [24, 25].

In TJ-II, the steepest plasma gradients are located at the plasma radius $\rho \approx 0.7$ whereas the edge velocity shear layer is located at $\rho \approx 0.9$. This decoupling between the locations of maximum gradient and edge sheared flows makes TJ-II a unique device to study the possible

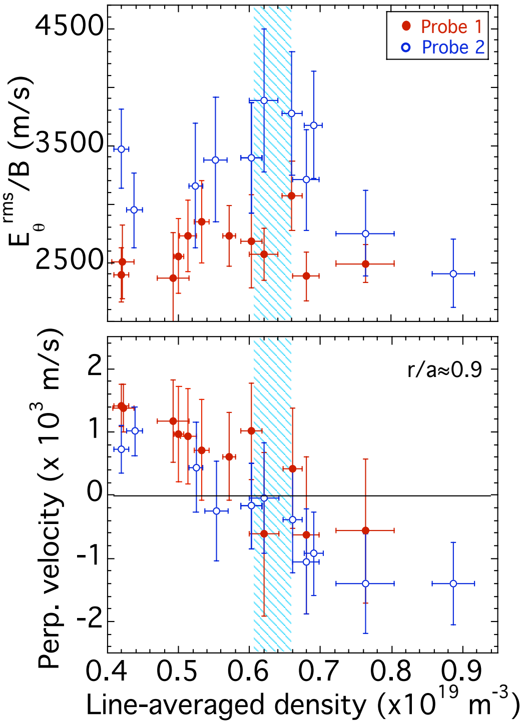

Figure 5. Averaged electric field fluctuations and perpendicular velocity measured at two toroidal locations and at approximately the same radial position (ρ≈0.9) as a function of plasma density.

role of plasma gradients in the development of the universal edge sheared flows in fusion plasmas; measurements with a two-channel fast frequency hopping reflectometer have shown that the radial origin of the edge shear layer is linked to the plasma region with maximum density gradient, expanding towards the edge until the edge shear flow is fully developed [26].

Different edge plasma parameters were simultaneously characterized in two different toroidal positions using two similar multi-Langmuir probes installed on fast reciprocating drives during spontaneous and biasing induced transitions to improved confinement regimes [27]. The fluctuation levels and the turbulent transport increase as density increases up to the critical value for which sheared flows are developed. For densities above the threshold, fluctuations level and the turbulent transport slightly decrease and the edge gradients become steeper. Edge sheared flows are developed at the same threshold density in the two toroidal positions (Figure 5).

Figure 6 illustrates the dependence of the toroidal floating potential cross-correlation on the line-averaged density. It is observed that the cross-correlation depends on the density, being larger in the proximity of n ≈ 0.6 x 10^{19} m^{-3}, which corresponds to the threshold density for shear flow development for the selected plasma configuration. The increase of correlation with plasma density results mainly from the rise in the correlation at low frequencies (below 20 kHz).

Confinement improvement has been provoked by external plasma biasing. The effect of the increased radial electric field shear on the radial profiles has been investigated [28] and so have long-range correlations. Experimental findings show clearly an increase in the cross-correlation in floating potential signal (but not in density fluctuations) during the biasing phase. These results show that the increase in the degree of long-range toroidal correlation (for potential fluctuations) is strongly coupled to the presence of radial electric fields (Figure 7).

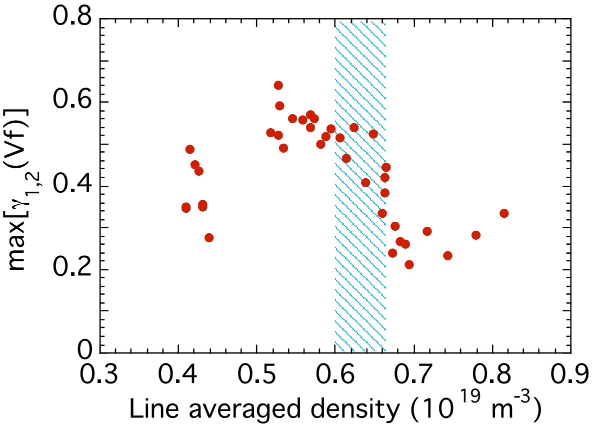

Figure 6. Maximum value of the cross-correlation between floating potential signals measured at approximately the same radial positions of both probes (ρ≈0.9) as a function of plasma density.

The behaviour of the bicoherence, computed for appropriated quantities (such as the fluctuating poloidal electric field, measured by Langmuir probes), shows an increase in non-linear coupling effects during forced confinement transitions (induced by biasing) [29]; however, this increase in the auto-bicoherence was significant only in a narrow radial range in contrast to the fluctuation levels which were affected over a very broad radial extension. A reduction of the Reynolds stresses component as a result of the lower turbulence level was observed. However, the 'phase coherence' between the fluctuations (both radial-parallel and radial-poloidal Reynolds stress components as shown in Figure 9) was strongly enhanced inside the plasma. The experimental findings show the dual role of sheared ExB flows as a fluctuation stabilizing term as well as an agent affecting the parallel momentum balance via turbulence modification.

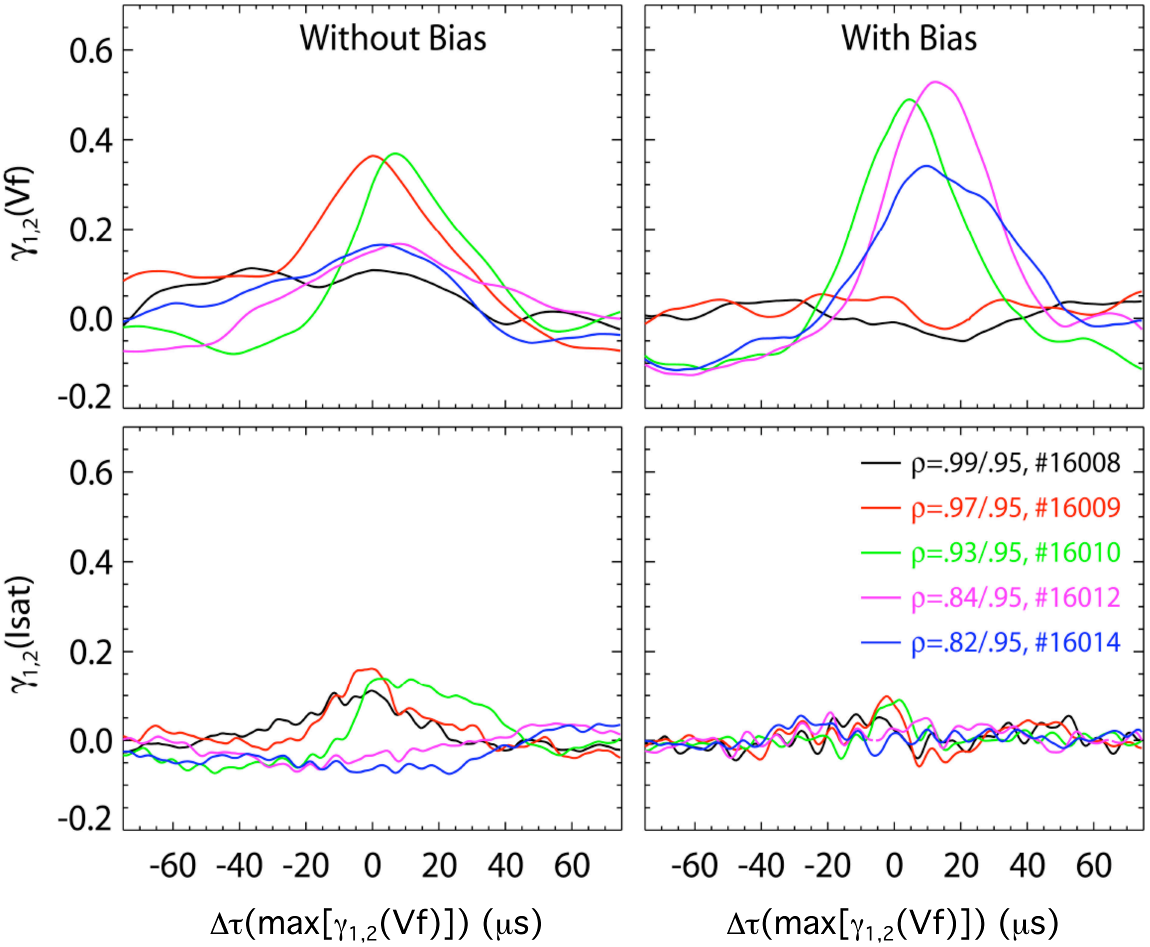

Figure 7. Cross-correlations of floating potential (top) and saturation current (bottom) without (left) and with (right) biasing.

It remains as an open question to clarify which mechanisms can provide such long-range correlations in plasma potential but not in density fluctuations. Turbulence driven flows (zonal flows) are expected to show such correlations in the order parameter related with the shearing rate (i.e. electric fields) and so an amplification of such correlation via electric fields would be also expected. Actually, the experimental results can be theoretically understood by incorporating the dynamics of zonal flows to the second-order transition model for the emergence of the plasma edge sheared flow layer [30]. Ion orbit loses might also trigger localized perturbation in the plasma potential, whose 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.

Comparative studies with other devices are crucial to assess the importance of multi-scale physics in the development of sheared flows and transport and the role of magnetic configuration (e.g. influence of safety factor).

3.2 Transitions in NBI (Li-coating) plasmas

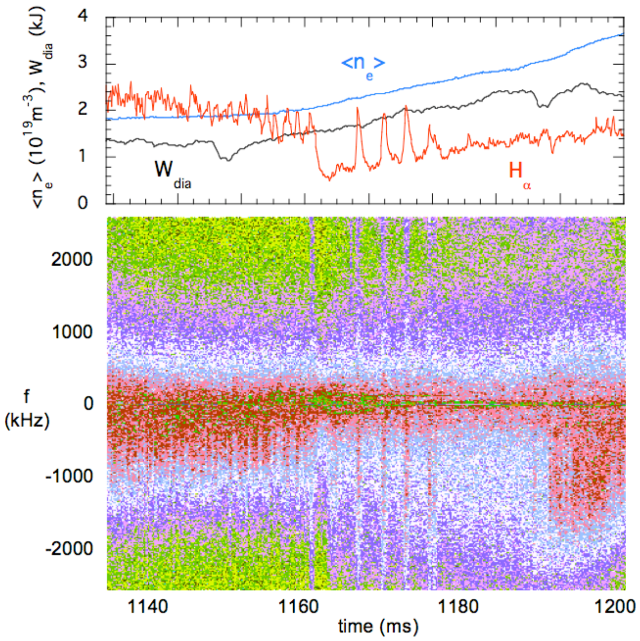

Figure 8. Time evolution of plasma density, stored energy, and Halpha emission during the L-H transition (top). Power spectra of broadband fluctuations measured by reflectometry (bottom).

The operation under Li-coated wall allows the plasma-wall interaction to decrease strongly with the subsequent reduction of CX, ionization and radiative losses in the edge [31]. Due to this new power balance and to the decrease of neutral population, the experiments in NBI heated plasmas have shown evidence of additional bifurcations between the usual and the improved confinement regime. These transitions, which happen spontaneously, are characterised by an increase of plasma density and stored energy, measured respectively by interferometry and diamagnetic coils (see figure 8). This confinement improvement is accompanied by a reduction in the Hα emission, showing a decrease of the outward particle flux, together with the reduction of the level of broadband fluctuations, as measured by both reflectometry and Langmuir probes (Fig. 8). Figure 9 shows the density profiles before and after the transition, as measured by Thomson scattering diagnostic in four discharges similar to that shown in Fig. 8. A steeper density gradient is developed just at the transition. The electron temperature profile remains unchanged within the error bars. A negative radial electric field (in the range of 100 V/ cm) is developed during the NBI phase and it becomes more negative after the transition. In some discharges, edge instabilities are developed about 10 ms after the above described transition, as observed in Hα, probe and reflectometry signals (see Fig. 8). These events are propagating radially (inwards and outwards) with velocities in the range of 1 km/s. All these phenomena are characteristic of the transition to H mode.

The appearance of this additional TJ-II bifurcation, at present under investigation, would make TJ-II a unique experiment to study the two-step process in the development of edge sheared flows in fusion plasmas, since both types of transitions are present in our device (see [32] and references therein).

4.- Summary and conclusions.

Strong improvement of plasma confinement has been observed in the TJ-II stellarator after Li-coating, in comparison with the operation under Boron coated walls. The beneficial Li properties for plasma-wall interaction have a strong effect on this device that presents a helical limiter very close to the magnetic axis, which receives the strongest particle and heat fluxes. The outstanding results are the density control in formerly collapsing NBI discharges and the improvement of particle and energy confinement. The properties of Li as a plasma facing material in fusion devices are explored in these experiments, which is relevant for the future fusion reactors, where Li could be used for liquid divertor or for coating some in-vessel components.

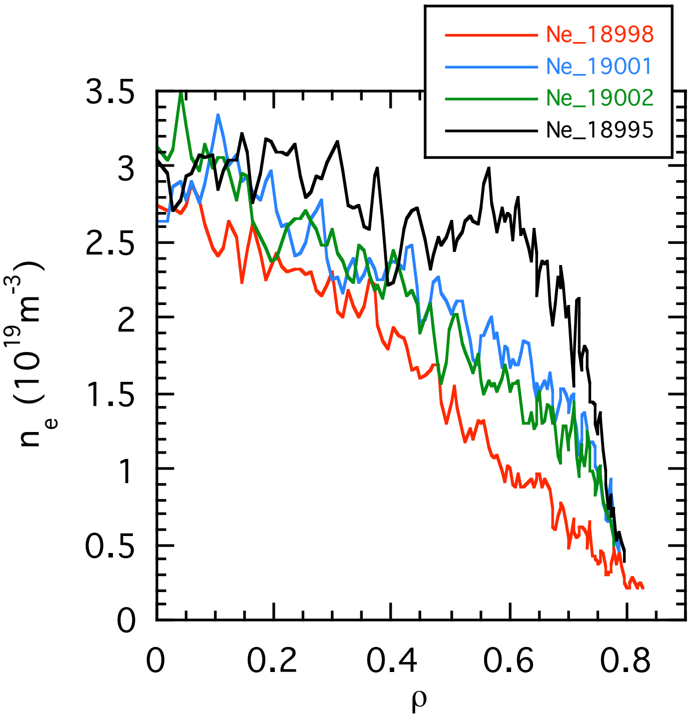

Figure 9. Evolution of the density profile during L-H transition

The technique used for lithiumnization is the evaporation by ovens, and the Li is homogenised in the vessel walls by the plasma itself. The wall properties after Li coating are strongly changed and, remarkably, they increase the H retention capability, thus improving the density control. The O gettering is still maintained by the boron layer that is deposited under the Li one. A key ingredient for understanding the operational improvement is the change of profile radiation under Li coated wall. The edge radiation is observed to fall, which avoids the power unbalance that produces the low radiation collapse.

During the high density NBI operation, a transition to an improved confinement regime is observed, characterised by the increase of diamagnetic energy, the decrease of Hα emission, the drastic reduction of turbulence, and the development of steep density gradients. In some discharges, edge instabilities are triggered about 10 ms after the transition, that are recorded by Hα emission monitors, reflectometry and Langmuir probes.

This type of spontaneous transitions is added to the ones that happen at lower densities, n ≈ 0.6 x 10^{19} m^{-3}, which corresponds to the shear flow development. These transitions are also provoked by biasing. During these lower density transitions, an increase in the cross-correlation in floating potential signals measured by probes located at distant toroidal positions is found. These results show that the increase in the degree of long-range correlation (for potential fluctuations) is strongly coupled to the presence of radial electric fields.

In this way, TJ-II has become a unique experiment to study both types of phase transitions.

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