On the influence of the magnetic topology on transport and radial electric fields in the TJ-II stellarator

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Abstract. The influence of the magnetic topology on plasma profiles and turbulence has been investigated in ECH plasmas in the stellarator TJ-II, taking advantage of the flexibility of this almost shearless device. A wide range of edge rotational transform values can be attained, but the rotational transform profile can also be tailored by inducing currents using both ECCD and two sets of OH coils. In this way it is possible to introduce rational surfaces inside the plasma and to modify the magnetic shear to examine their effect on confinement. Kinetic effects and flux changes due to the presence of resonances and ECRH are responsible of the formation of barriers in the plasma core, while the shear flow is a key ingredient in the plasma edge. The results here shown offer wide and valuable information to assess multiple mechanisms based on neoclassical/turbulent bifurcations and kinetic effects as candidates to explain the impact of magnetic topology on radial electric fields and confinement.

1.- Introduction and description of the problem.

Beyond the influence of magnetic configuration on transport in the several collisionallity regimes, the magnetic topology is a very important ingredient for plasma confinement in magnetic traps. The presence of rational surfaces that break the magnetic topology of nested flux surfaces and introduces magnetic islands and ergodic zones must affect on particle and heat fluxes as well as on turbulence and electric fields.

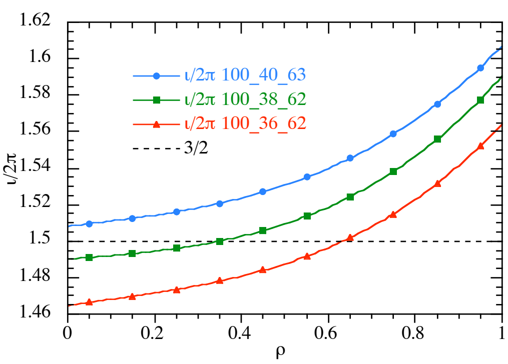

Figure 1. Rotational transform profiles of the configurations used for the scan.

It is well known that the presence of rational magnetic surfaces in magnetic confinement plasmas can create transport barriers in the position located in the inner part of the rational surface [1]. Transport barriers close to resonant magnetic surfaces have been observed in tokamak plasmas in confinement region (internal transport barriers, ITB) and plasma edge (ETBs) (see e. g. [2] for a presentation of ITBs in RTP and [3] for a review of ITBs in tokamak plasmas) as well as in stellarator plasmas (see [4] and [5] for ETBs, [6] and [7] for ITBs, and a review of ITBs in stellarators can be found in [8]). Two different explanations for the appearance of ITBs have been considered. One based upon the generation of *ExB* sheared flows in the proximity of rational surfaces that can decorrelate turbulent structures and, hence, anomalous transport [9], creating a transport barrier (as shown in [4]). The other explanation attributes the ITB to a rarefaction of resonant surfaces in the proximity of low order rationals, which is expected to decrease turbulent transport [10]. This idea has been used to explain several experimental results obtained in tokamaks (see [2] and [11]).

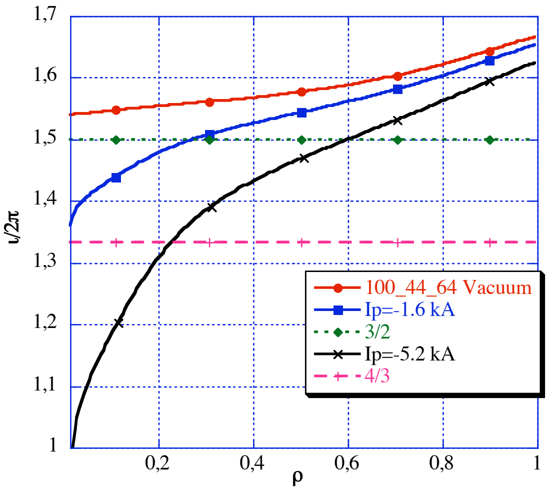

Figure 2. Vacuum rotational transform profile and modified by OH current.

The effect of rational surfaces in stellarators has been controversial. On the one hand it has been claimed that its presence inside the plasma column was prejudicial because they tend always to degrade the confinement, but locating the rotational transform profile close to a rational value would improve the confinement in a shearless device, due to the same mechanism of rarefaction explained above [12]. On the other hand, it has been shown that low order rational surfaces can create ITBs in stellarators, hence improving the confinement. As it will be shown in this work, the low order rational surfaces can trigger electron heat ITBs for different magnetic shear values and are accompanied by the appearance of positive sheared electric fields.

A shear in the radial electric field can be driven in several ways: By the turbulence itself [13] via Reynolds stress and shear generation in the mean flow; by neoclassical mechanisms due to the difference between ion and electron fluxes [14]; and by kinetic effects induced by electron cyclotron resonance heating (ECRH) through enhancement of the outward electron flux [15].

Taking advantage of the flexibility of the stellarator TJ-II we have investigated the influence of the magnetic topology on confinement and electric fields in ECRH plasmas in this almost shearless device. Those plasmas are characterized by having peak electron temperatures $T_e \approx 1$–2 keV and low densities $n_e \approx 1 \times 10^{19}$ m^{-3}. Therefore, we are in the low collisionality regime in the plasma core. A wide range of rotational transform values can be attained ($\iota/2\pi$=0.9 to 2.1) by changing the currents that circulate in the helical and circular coils of the central conductor of TJ-II. In this way it is possible to introduce rational values of rotational transform in the plasma and to study their effect on confinement and related items, like turbulence and electric fields.

It is also possible to induce currents by using two sets of Ohmic coils available in TJ-II and to drive non-inductive currents using ECRH. In this way the rotational transform profile can be tailored and the magnetic shear can be varied to some extent.

The effect of magnetic topology on transport is studied experimentally in TJ-II from two different perspectives: 1) Kinetic effects, related to low collisionality, are dominant in the plasma core where the plasma is in the long mean free path regime and HIBP gives us the value of electric potential; and 2) *ExB* turbulent transport is best studied in the edge, where Langmuir probe measurements are available and biased electrodes are applied. For low injected power (below 300 kW), there are not indications of barrier formation in plasmas whose magnetic configurations do not contain low order rationals; but peaked temperature profiles at low density and high absorbed power density can appear, showing an enhanced heat confinement attributed to the appearance of the electron root in TJ-II [16].

This paper, which shows the results of introducing low order resonances inside the plasmas using the above described mechanisms, is organized as follows: Section 2 is devoted to the study of the effects of positioning low order resonances in the plasma core, Section 3 deals with kinetic effects that are necessary to explain the heat confinement improvement shown in section 2; Section 4 regards the effects of rationals close to the edge and the conclusions come in Section 5.

2.- Effects of low order rationals in plasma core.

We have positioned low order rational surfaces close to the plasma core in TJ-II ECRH plasmas by two methods: We have performed a magnetic configuration scan and we have induced current in order to modify the rotational transform profile. Electron internal heat transport barriers (eITB) appear in both cases when the low order rational surface is close to the plasma core region (effective radius $\rho \approx$ 0.2-0.3), while they disappear when the rational surface is positioned at outer positions [7]. No barriers are observed either in particle transport or in the ion channel.

An important difference between these two methods is that the OH-induced current introduces a magnetic shear, especially in the plasma core, while in the configuration scan the vacuum rotational transform profile is only slightly modified by boostrap current (less than 1 kA in absolute value). Thus, the effect of low order rationals is studied in low and moderate shear environments.

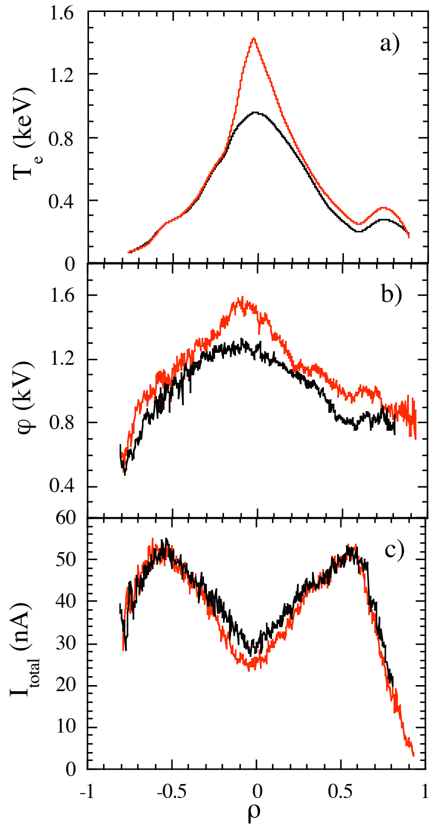

Figure 3. Temperature, potential and HIBP-beam intensity profiles, with (red) and without (black) e-ITB.

The vacuum rotational transform profiles that correspond to the explored magnetic configurations are shown in Figure 1, where the position of the (n=3/m=2) resonance can be seen. The shot performed in configuration with $\iota(0)/2\pi\approx1.508$ does not present eITB, the one with $\iota(0)/2\pi\approx1.464$ is an intermediate case and the eITB appears during the shot, depending on bootstrap current, while the shot performed in configuration with $\iota(0)/2\pi\approx1.490$ presents a steep temperature gradient during the whole discharge.

The formation of eITBs when the rational surface position is moved in a single shot by inducing plasma current by OH-coils is characterized by a sudden increase in the core electron temperature and in the core plasma potential [6]. Figure 2 shows the estimated rotational transform profile when OH current is induced just in two moments when the jump in temperature happens. It is shown that the n=3, m=2 and the n=4, m=3 resonances are close to plasma core at those times. The measured radial electric field E_r in plasmas with e-ITB is in the range of 10-15 kV/m, three times the value without barrier, which is in the range of 4-5 kV/m. The rotation velocity in the plasma core is three times faster in the case with e-ITB, in agreement with the ion-momentum balance equation. The estimated E_rxB shearing rates in the discharges with low order rationals are in the order of 10^5-10^6 s^{-1} and the formation of eITB has been observed with positive and negative magnetic shears. We are showing in Fig. 3: a) the temperature profiles in plasmas with and without barrier; b) the potential profile measured by HIBP for the same cases as before, demonstrating that a stronger positive radial electric field appears in the core; and c) the total beam intensity measured by HIBP, which is proportional to plasma density, showing that the central density is lower in the case with barrier in this discharge. Transport analysis performed with the modified predictive transport code Proctr shows a reduction of core heat diffusivity by a factor 2 [7]. A reduction of turbulent transport due to the sheared *ExB* flow is claimed to be its cause in Refs. [17] and [18], and the modification of neoclassical transport is postulated in Ref [19]. In the first case the important magnitude is the amount of shear flow, i.e., the quantity dE_r/dr, being the value of electric field in the second one. In TJ-II, the mechanism for heat transport reduction must be compatible with no particle confinement enhancement.

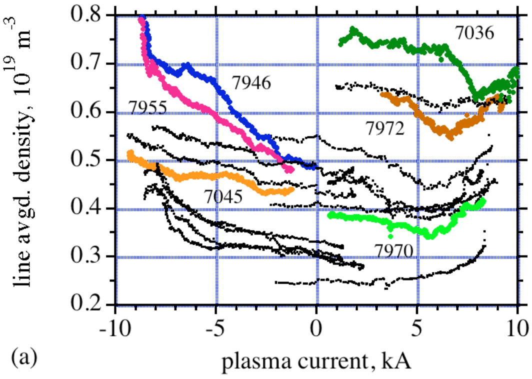

Figure 4: Effect of OH-plasma current on line density.

Finally, OH-coils have been used to induce relatively large positive and negative currents up to |Ip| < 10 kA, allowing several rational surfaces to cross entirely the plasma column [20]. It is shown that the negative shear, $s=(1/r)(dq/dr)=-(1/r)(d(\iota/2\pi)/dr)$, that is created in TJ-II by driving negative currents, correlates with improved confinement, causing that the profiles become wider in the long time scale, while a non-monotonic behaviour of plasma confinement versus shear is observed for positive currents, as can be seen in Fig. 4.

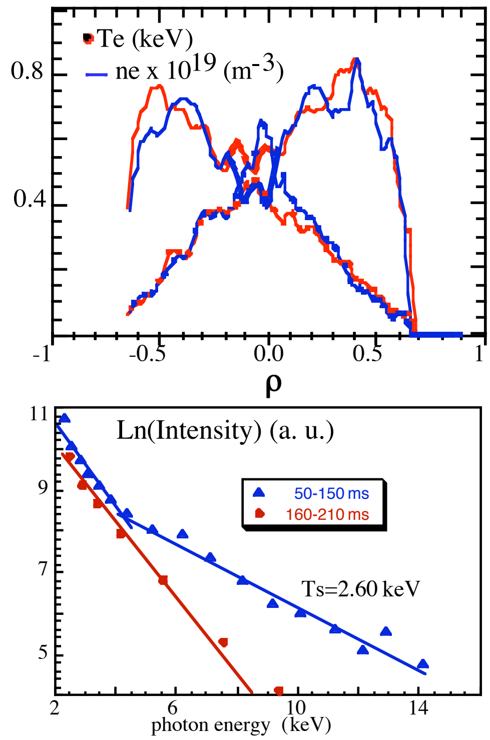

Figure 5. Electron density and temperature profiles for the cases with (blue) and without (red) enhanced particle losses (Top). SXR spectra show a superthermal tail in the case without enhanced losses.

The signature of the low order resonances that cross the plasma can be seen in the line density evolution (see Figure 4) as well as in thermal signals. Some strong perturbation of the signals can be correlated with the time when resonances travel along the confinement zone (ρ ≈ 0.4-0.7).

3.- Kinetic effects and transport.

Rational surfaces modify the trapping and detrapping rates of ripple-trapped suprathermal electrons and, hence, provoke fast changes of emissivity profiles [15] that take place at well defined radial positions, close to low order rational surfaces. Those changes are correlated with modifications of the electron distribution function, as deduced from SXR spectra. Both phenomena have been identified as signatures of transitions between high and low direct losses regimes that are also manifested in a more hollow density profile (see Fig. 5), showing an increase of outward radial electron flux. Magnetic topology also affects the radial transport of fast passing electrons, which can be confined near rational surfaces more than 50 ms. All these facts and the ones shown in the previous Section point to kinetic effects induced by ECRH and the presence of rational surfaces as the necessary ingredients to explain the observed heat transport modification in the plasma core.

The perturbed electron flux, which is much larger than the ion one, is given by: $\Gamma_e(E_r)=\Gamma_e^{NC}(E_r)+\Gamma_e^{TURB}(E_r)+\Gamma_e^{ECH}(E_r)+\Gamma_e^{ISLAND}(E_r)$. In this expression, the neoclassical, the ExB turbulent, the ECH-induced fluxes and the induced by the rational surface are considered. The experimental results of TJ-II presented in former section show that the cooperation of the third and fourth terms is necessary to create the radial electric field able to reduce heat transport.

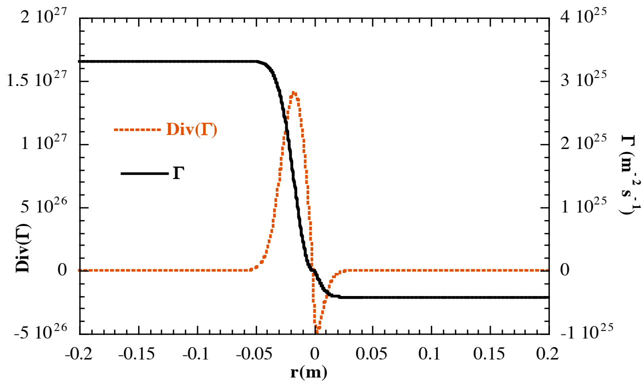

Figure 6. ECH-induced electron flux and its divergence.

The estimation of the flux through the magnetic surface needs a detailed knowledge of the magnetic topology. A recent calculation for tokamak plasmas shows a strong modification of electron and ion fluxes and hence, of ambipolar electric field [14]. An approximated estimation can be done if the modification of ion flux due to the presence of the rational surface is negligible in comparison with the electron one. In this case, the electric field will be given by $E_r \approx (T/e)(n'/n - T'/2T)$.

An approach based on Langevin equations has been recently developed to calculate the ECH induced flux [21]. We have estimated the linear instantaneous ECH-induced flux (created when ECH is switched on in a hot plasma) disregarding the viscosity, the evolution of distribution function (assumed Maxwellian) and the effect of collisions, and assuming that all the particles that enter the loss cone are lost. The flux and its divergence are plotted in Fig. 6. This extra flux causes the onset of an electric field that keeps $\Gamma_e=\Gamma_i$, therefore stopping electron flux, and increases the heat confinement. As a first step to estimate the time evolution of the flux and the field, we evolve the coupled equations: $m\,d\Gamma/dt=-enE-p'$; $dE/dt=(e/\varepsilon)\Gamma$; $(3/2)(dp'/dt)=-(q''+q'/r-q/r^2)+w'$. Here p is the plasma pressure, and q is the heat flux, $q=(5/2)(p/n)\Gamma-(3/2)\chi p'$. In absence of collisions and viscosity and keeping constant the distribution function, an oscillating behaviour of particle flux and electric field with the plasma frequency appears, therefore the typical time scale for the modification of the field is $\tau\sim1/\omega_p$, according to this model. The experimental results show a much longer typical time (tens of μs). This discrepancy can be due to the fact that the deformation of electron distribution function is not considered. Nevertheless the qualitative behaviour is explained: an outward flux that causes the onset of a positive electric field appears. Moreover, accordingly to the former calculations, the outward ECRH-induced flux is proportional to absorbed power density. The experimental data show a clear

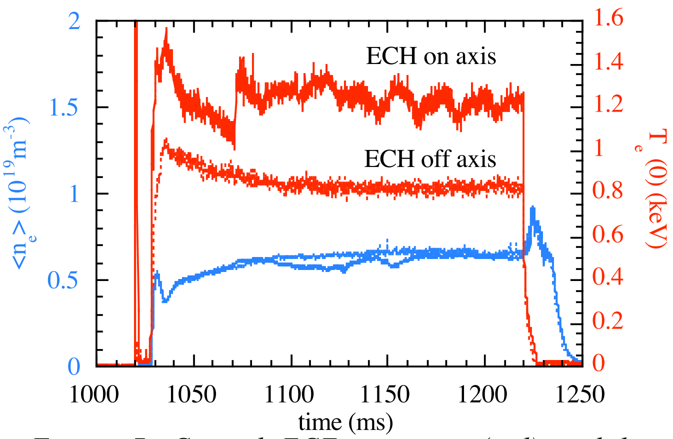

Figure 7. Central ECE emission (red) and line density (blue) evolution for two discharges with on- and off-axis ECRH. The temperature jump happens in the discharge with on-axis heating.

dependence on that magnitude, as can be seen in Figure 7, where two TJ-II discharges with the same magnetic configuration and the same plasma density are displayed. One of them has on-axis power deposition profile while the other is off-axis heated. It is seen that eITB appears in the shot with on-axis heating in which the absorbed power density is larger (about 5 W cm-3) than in the case with off-axis heating (about 1 W cm-3). The pump-out will be stronger in the first case and so will be the outward flux. This flux, together with the fact that the value of rotational transform profile is close to the rational is enough to trigger the eITB.

4.- Rationals close to the edge.

We have also positioned rational surfaces close to the edge, where their effects are diagnosed by Langmuir probes and HIBP. In this plasma region, kinetic effects must be weaker since the collisionality is higher. The presence of natural resonant surfaces has been detected through a flattening observed in plasma-edge ion saturation current profiles and through the floating potential becoming more positive and showing a significant radial variation. Quasi-coherent modes (of about 70 kHz), associated with the existence of rational surfaces, have been also observed in TJ-II.

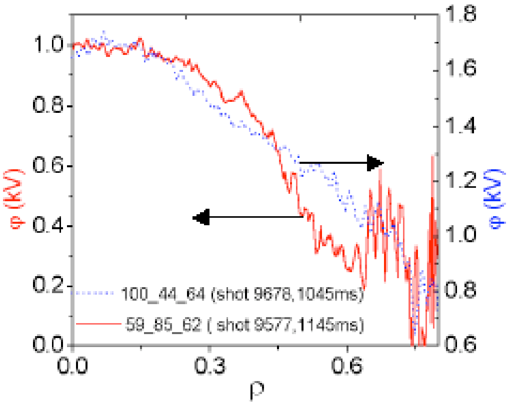

Figure 8. Electric potential profiles in presence of n=4, m=2 resonance in the plasma periphery (red) and without low order resonances (blue).

Recently, experimental evidence of significant radial gradients in the cross-correlation between parallel and radial fluctuating velocities as well as a dynamical coupling between edge instabilities and parallel flows has been reported near the LCFS in JET tokamak and TJ-II stellarator [22]. These gradients are mainly due to the radial variations in the level of poloidal electric field fluctuations and in the cross-phase coherence. Therefore, the Reynolds stress seems capable of sustaining a non-negligible parallel mean flow in the plasma edge region, as was predicted theoretically [13]. Furthermore, this mechanism is expected to be particularly relevant in plasma regions with a unique magnetic topology, e. g., near the LCFS and in the proximity of rational surfaces. In these plasma regions strong gradients in the level of fluctuations are expected.

In fact, structures in edge plasma profiles have been observed when low-order rational surfaces are present: Radial plasma-potential profiles measured by the HIBP present evidence of structures in configurations with low order rational surfaces (Figure 8). A possible explanation for such a flow structure near rational surfaces is the coupling of flow generation and turbulence. This mechanism would be consistent with the magnitude of the shearing rates being close to the critical value for reducing fluctuations in the plasma edge. Therefore if a magnetic island can enhance the shear flows, reduction of fluctuations via *ExB* shear is possible.

The changes in the measured profiles of the floating potential have been interpreted as an increase of the sheared *ExB* flow linked to the radial location of rational surfaces. The experimental results in TJ-II illustrate the impact of rational surfaces in the generation of *ExB* sheared flows and, therefore, how they can act as a potential trigger for transport barriers. Local turbulent *ExB* driven flows are significantly modified in the proximity of rational surfaces. In the case of measurements taken in the proximity of the (n = 4/m = 2) resonant surface, located near the plasma boundary, the local *ExB* fluctuation particle flux shows a reverse direction (from outwards to inwards). This modification is due to a change in the phase relation between density and electric field fluctuations. The change in the *ExB*

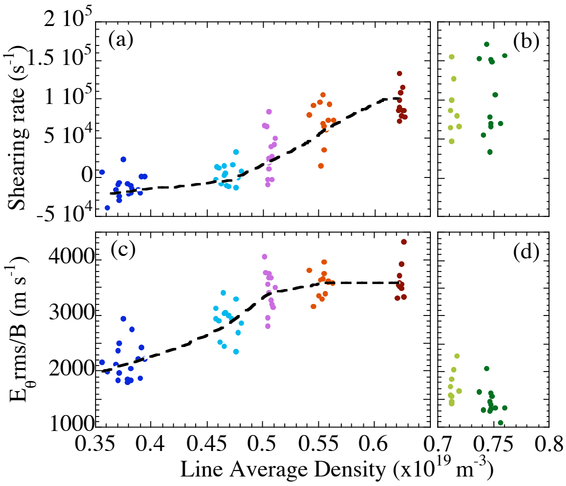

Figure 9. Shearing rate vs. line density without (a) and with (b) polarised electrode and their corresponding turbulence levels (c,d).

turbulent transport is related to the radial extension of the resonant region that depends on the order of the rational surface and on magnetic shear. The presence of *ExB* shear flow at the boundary of the magnetic island is, therefore, a candidate to explain the observed link between the location of transport barriers and low-order rational surfaces in fusion devices [23], [24].

We have also obtained the first experimental evidence of coupling between the development of sheared flows and the structure of turbulence close to the plasma LCFS [25]. The experiments have shown that the development of the naturally occurring edge velocity shear layer requires a minimum plasma density (or/and minimum level of plasma turbulence). Although experimentally the external control is the plasma density, it would be more appropriate to characterize experimental results in terms of edge plasma gradient (e.g. I_s gradients): the higher the central density, the steeper the density gradient. The perpendicular velocity changes sign above the critical density value due to the development of the natural shear layer (and so does the radial electric field). Below the critical density the shear layer does not exists at least up to 3 cm inside the LCFS ($\rho \approx 0.8$). These results indicate that the evolution of parallel flows, the level of poloidal electric field fluctuations and the generation of *ExB* sheared flows are coupled. The correlation between the increase in the edge-shearing rate with an increase in the turbulent velocity fluctuations (E_θ/B) suggest that a minimum level of turbulent kinetic energy is needed in the plasma edge to trigger the spontaneous formation of the sheared flows.

The resulting shearing rate obtained in the above mentioned experiments is comparable to the one required to trigger a transition to improved confinement regimes with reduction of edge turbulence, suggesting that spontaneous sheared flows and fluctuations keep themselves near marginal stability (see Fig. 9) [26]. While these results support the importance of turbulence to understand the observed interplay between magnetic topology and transport in the edge, the time scales of the perturbation in density and plasma potential (50-300 μs) measured by HIBP and its localization within the ECH deposition profile, support the idea of the dominant role of ECH convective fluxes in the formation of e-ITBs in the plasma core of TJ-II.

6.- Conclusions.

All the mentioned TJ-II results offer wide and valuable information to assess multiple mechanisms based on neoclassical/turbulent bifurcations and kinetic effects as candidates to explain the impact of magnetic topology on radial electric fields and confinement.

In ECRH plasmas, low order rationals when positioned close to plasma core ($\rho < 0.3$) trigger electron heat transport barriers that are characterized by presenting a steep temperature gradient with a strong reduction of heat diffusivity and an increase of superthermal electron population. A strong positive electric field is created by the enhancement of electron flux due to ECRH and the presence of rational surface. Therefore, the necessary ingredients to create the barrier are the pump-out and the rational surface.

The presence of low order rational surfaces in the confinement region ($0.4 < \rho < 0.7$) cannot create a barrier in the plasmas used in this work, with low magnetic shear. Moreover, when the rational crosses the plasma column, fast falls in the line density as well as in thermal signals appear, showing a transient degradation of confinement.

The rationals close to the edge are able to modify the structure of radial electric field and turbulence. The level of turbulence in the plasma edge tends to create sheared flows that regulates the turbulence, sustaining the plasma in a state of marginal stability. The structure of the sheared flow and, hence, of the turbulence, is modified in presence of the resonance surface or by creating an electric field polarising an electrode inside plasma edge. The created sheared flow is able to overcome the turbulence level and, hence, to reduce the anomalous transport in the inner part of the rational surface, thus creating a transport barrier.

Acknowledgements
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[1] KOIDE, Y., KIKUCHI, M., MORI, M., et al. Phys Rev. Lett. 72 (1994) 3662
[2] LOPES-CARDOSO, N., et al. Plasma Phys. Control. Fusion 39 (1997) B303
[3] WOLF, R.C., Plasma Phys. Control. Fusion 45 (2003) R1
[4] HIDALGO, C. et al. Plasma Phys. Control. Fusion 42 (2000) A153
[5] OYABU, O., et al. Phys. Rev. Lett. 84 (2000) 103
[6] ESTRADA, T., et al., Plasma Phys. Control. Fusion 46 (2004) 277
[7] CASTEJÓN, F., et al., Nucl. Fusion 44 (2004) 593
[8] FUJISAWA, A., Plasma Phys. Control. Fusion 45 (2003) R1
[9] TERRY, P.W., Rev. Modern Phys. 72 (2000) 109
[10] ROMANELLI, F., and ZONCA, F., Phys. Fluids B 5 (1993) 4081
[11] GARBET, X., Nucl. Fusion 43 (2003) 975
[12] BRAKEL, R., Nucl. Fusion 42 (2002) 903 and references therein.
[13] DIAMOND, P., et al., Phys. Rev. Lett. 72 (1994) 2565
[14] SHAING, K.C., HEGNA, C.C., CALLEN, J.D., and HOULBERG, W.A., Nucl. Fusion 43 (2003) 258
[15] OCHANDO, M.A., MEDINA, F., and THE TJ-II TEAM, Plasma Phys. Control. Fusion 45 (2003) 221.
[16] CASTEJÓN, F., et al., Nucl. Fusion 42 (2002) 271-280
[17] FUJISAWA, A., et al. Phys Rev. Lett. 82 (1999) 2669
[18] MINAMI, T., et al. Nucl. Fusion 44 (2004) 342
[19] MAASBERG, H., et al., Phys. Plasmas 7 (2000) 295
[20] LÓPEZ-BRUNA, D., et al., Nuclear Fusion 44 (2004) 645-654
[21] CASTEJÓN, F., EGUILIOR, S., Plasma Phys. Control. Fusion 45 (2003) 159-167
[22] GONÇALVES, B., et al., "On the momentum re-distribution via turbulence in fusion plasmas: experiments in JET and TJ-II". EX/P4-5. This Conference.
[23] PEDROSA, M.A., et al. Plasma Phys. Control. Fusion 43, (2001) 1573
[24] HIDALGO, C., et al., New Journal of Physics 4 (2002) 51.1]
[25] PEDROSA, M.A., et al. "Radial electric fields and improved confinement regimes in the TJ-II stellarator". EX/P 6-21. This Conference.
[26] HIDALGO, C., et al., Plasma Phys. and Control. Fusion 46 (2004) 287