Influence of low order rational magnetic surfaces on electron internal transport barriers in the stellarator TJ-II

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Introduction

In stellarator devices, transitions to improved core electron heat confinement are established in conditions of high ECH power density and are characterized by peaked electron temperature profiles and large radial electric field and shear in the inner plasma region [1-8]. These transitions have been often referred as Neoclassical or electron Internal Transport Barriers (N-ITB or e-ITB) [1,2,4,6] or as "electron root" feature [3,8]. The specific characteristics of TJ-II, i.e. low magnetic shear and high magnetic configuration flexibility allow us the control of low order rational surfaces position within the rotational transform profile and, therefore, the study of how the magnetic topology affects e-ITB formation. e-ITBs can be easily triggered by positioning a low order rational surface at the plasma core region [6]. As it is discussed in [7], the key element to improve heat confinement is a locally strong positive radial electric field, which can result from a synergistic effect between enhanced electron flux through radial positions around the low order rational surface and pump out mechanisms in the ECH deposition zone. In this way, e-ITBs are achievable at higher plasma densities, reducing the ECH power per particle threshold. In this work we compare the characteristics of the e-ITBs triggered by two rational surfaces, n/m=3/2 & 4/2.

Experimental results

The characteristics of e-ITBs triggered by the n=3/m=2 rational surface are already described in [6,7] and can be summarized as follows. At the transition, the electron temperature, measured by ECE and Thomson scattering, and the plasma potential, measured by HIBP, increase in the plasma core region ($\rho < 0.3$), increasing substantially -in a factor of three- the radial electric field. These magnitudes remain almost unchanged at outer radii. The

increase in the central electron temperature depends on the plasma density and ranges from 40% at low densities $\langle n_e \rangle \approx 0.5 \ 10^{19} \ m^{-3}$ to 15% at higher densities $\langle n_e \rangle \approx 0.8 \ 10^{19} \ m^{-3}$. Measurements of the HIBP beam current indicate that, at the transition, as the plasma potential and electron temperature increase in the plasma core, the plasma density profile changes to a slightly more hollow profile. Assuming a constant ECH absorbed power, transport analysis indicates an improvement in the electron heat confinement in the plasma core. Besides, quasi-coherent modes are observed -in ECE and HIBP signals- where the E_rxB shear flows develop at the e-ITB formation. The mode can exist before or after the e-ITB phenomenon but vanishes as the barrier is fully developed [9]. Finally, transitions triggered by the 3/2 rational have no effect on the ion temperature.

e-ITBs triggered by the n=4/m=2 rational have been recently studied in TJ-II ECH plasmas. Firstly, it is important to mention that ECH discharges performed in magnetic configurations having the "natural" 4/2 resonance surface in the ι-profile in vacuum show a degraded confinement and very often an unstable evolution. However, the rational 4/2 with moderate magnetic shear can have a favorable effect on the confinement. e-ITBs triggered by the 4/2 rational have been obtained in a magnetic configuration with vacuum rotational transform above two by inducing a small amount of negative current, either ECCD or OH current. This negative current reduces the rotational transform mainly in the inner plasma region, crossing the rational 4/2 with increased negative magnetic shear.

e-ITB triggered by the 4/2 rational produces an increase in the electron temperature at the plasma centre of about 25% at relatively high line densities: 0.7-$0.9 \ 10^{19} \ m^{-3}$. Comparatively, the increase in the central electron temperature in e-ITBs triggered by the 3/2 rational is less pronounced - close to 15% - at similar densities: 0.7-$0.8 \ 10^{19} \ m^{-3}$.

Figure 1 shows an example of e-ITB triggered by the 4/2 rational in a discharge with $P_{ECH} = 350$ kW and in which the plasma current gradually increases due to OH induction. In this example the barrier is formed at about t =1100 ms and it is spontaneously lost and recovered. At the barrier formation, synchronized with the change in the electron temperature, we observe an increase in the ion temperature measured by CX-NPA diagnostic [10] and a reduction in the H_α signals. As the barrier is lost, ECE traces show a heat pulse propagating radially outwards. The evolution of the rotational transform profile shown in figure 1.d has been calculated with the ASTRA package considering that the only contribution to the current profile is the induced OH current, assuming Spitzer resistivity and imposing the

measured net plasma current evolution as boundary condition. SXR tomography diagnostic [11] shows a flattening in the profiles localized around $\rho \approx 0.4$ with a m=2 poloidal structure. An example is shown in figure 2. To highlight the poloidal structure of the flattening in the SXR profiles we have represented in figure 2 (bottom) the difference between the SXR tomographic reconstructions before and after the transition. This observation together with the absence of quasi-coherent oscillations indicate that in these discharges the magnetic island associated to the "natural" resonance n=4/m=2 does not rotate.
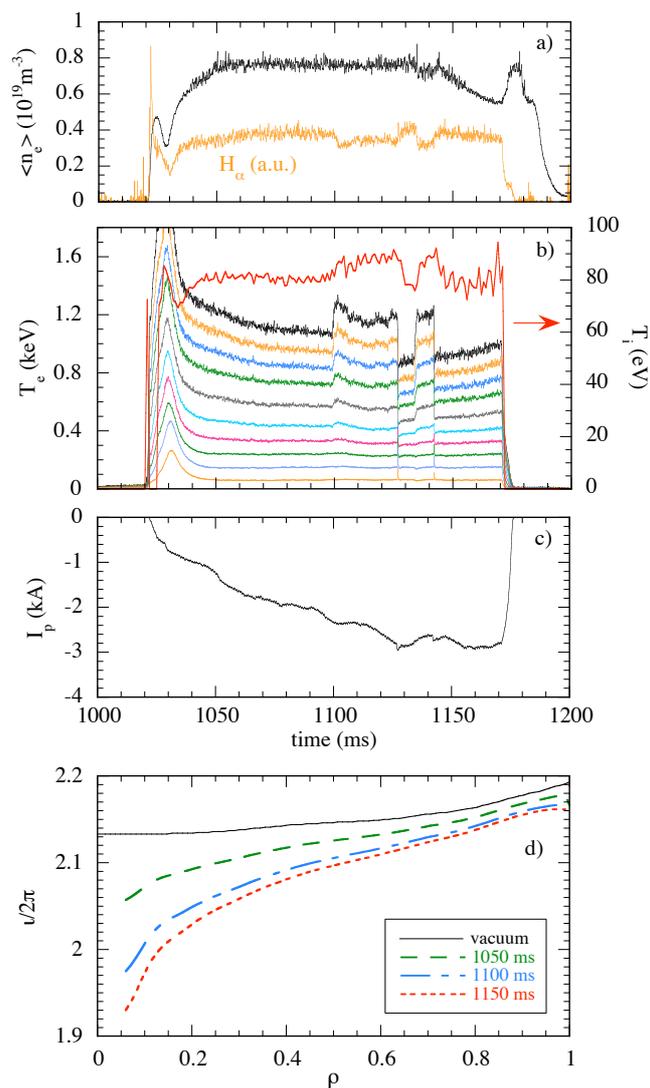

Figure 1: Time evolution of (a) line density and H_α signal; (b) electron temperature at several radii and ion temperature measured along a central plasma chord; and (c) net plasma current, in a discharge with OH induction; (d) ι-profiles at three different time instants.
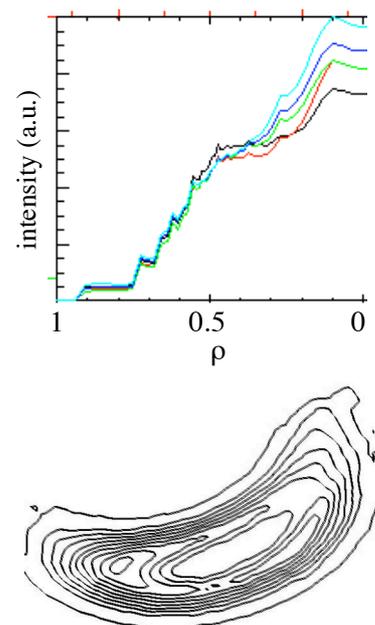

Figure 2: SXR profile evolution and difference between the tomographic reconstructions of the profiles before and after the transition.
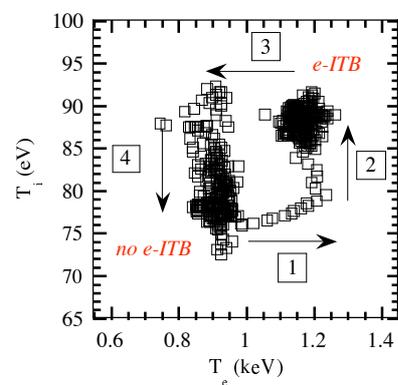

Figure 3: T_i vs. central T_e in the discharge shown in fig 1.

The plasma potential measured using the HIBP diagnostic increases in the central plasma region. Accurate measurements of plasma potential profiles have not been achieved in this magnetic configuration so far, what has precluded the characterization of the radial electric filed rise. An important result is the increase in the ion temperature, synchronized with the increase in the electron temperature (see figure 1.b). The change in the ion temperature is relatively modest (about 10-15 %), but it had not been observed previously either in TJ-II or in the other helical devices [8]. In figure 3 we have represented the ion temperature vs. the central electron temperature of the discharge shown in figure 1. It can be seen that the change in the electron temperature (1 & 3) precedes the change in the ion temperature (2 & 4) during both, barrier formation (1 & 2) and disappearance (3 & 4), being the delay of about 2-3 ms. Outer plasma chords have been scanned with the CX-NPA diagnostic in a series of reproducible discharges. Changes in T_i synchronized with T_e are still visible but lay within the error bar of the CX-NPA diagnostic.

The characteristics of these ECH plasmas, exclude collisional ion heating as the dominant mechanism for the ion temperature change. From power balance calculations we find that the collisional electron-ion power transfer is about 10 kW and it remains almost unchanged as the e-ITB develops. The radial electric field increases in transitions triggered by 4/2 or by 3/2, however, the transitions triggered by 3/2 have no effects on T_i. A possible mechanism to explain the ion temperature change would be linked to the resonances of the radial electric field [12]. These resonances modify the ion orbits and ion confinement, and the radial electric field needed for them to appear depends strongly on the rotational transform of the magnetic configuration.

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