Local effects of magnetic resonances in ECRH plasmas of the TJ-II Heliac

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Introduction

The characterization of local effects due to low order rational values of the rotational transform $\iota=1/q$ (they will be called resonances hereof) on plasma profiles is still an unresolved issue. There is cumulative evidence that collisional and turbulent transport are both dependent on the main radial electric field and vice-versa. Therefore, the 3D magnetic structure of stellarators is likely to be important in the transport problem. While it is a fact that magnetic resonances can be deleterious for transport in some circumstances, their effect is not clear otherwise from a general perspective. For instance, it is known that they can lower the power threshold to trigger L-H transitions [1], or even help in locating radially transport barriers, so a good characterization of their physics might make them, resonances, useful tools for confinement control.
One of the peculiarities of the Heliac design is its wide magnetic configuration space. In the TJ-II Heliac, $\iota=1/q$ values ranging from 1 to 2 can be easily accessed in low –vacuum– magnetic shear conditions. Other properties linked to magnetic configuration, like magnetic well or enclosed plasma volume, can be explored as well. So far, most of the attention has been paid to ι scans. These studies have been boosted with the commissioning of a system to perform dynamic magnetic configuration scans, where the offset of the ι-profile can be changed in a single (~300 ms) discharge at practically constant plasma volume and no ohmically induced currents [2,3]. In contrast with dynamic scans driven by the induction of ohmic currents, in these new scans the net plasma current behaves like in static configuration discharges. In what follows we inform about several experimental facts related with the non-destructive presence of resonances in ECH plasmas of the TJ-II Heliac.

Experimental results

The TJ-II Heliac allows for variations of the vacuum magnetic configuration spanning a rather large range in ι, see figure 1, by changing the values of the currents feeding the central conductors, circular (I_{cc}) and helical (I_{hx}). The ι-profiles are always quite flat with magnetic shear magnitude approaching 0.1 only near the plasma edge. Scans like the one shown in Fig. 1 (right) can be performed either statically, i.e., studying steady-state plasmas in similar discharges but different configurations; or dynamically, so in one single discharge the configurations are continuously changed from the beginning to the end of the discharge. All the results presented in this work refer to electron cyclotron resonance (ECR) heated plasmas (heating power in the range

300–600 kW) with line densities 0.5–1.0 x 10^{19} m^{-3}, central electron temperatures ~ 1 keV and ion temperatures ~ 0.1 keV.

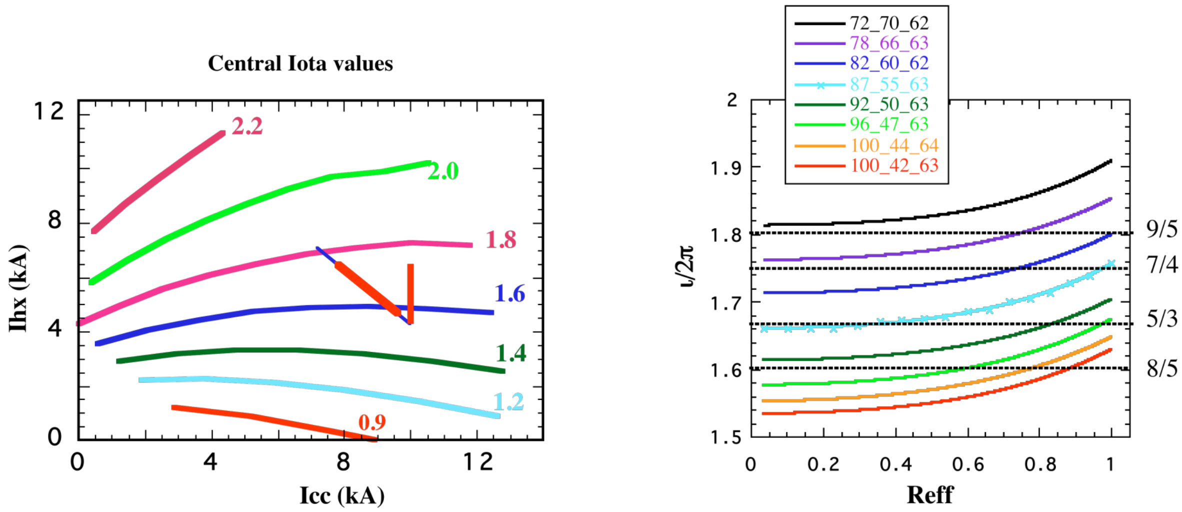

Figure 1. Left: configuration diagram of the TJ-II with central ι values as a function of the currents in the central conductors. Two line segments are examples of performed configuration scans. Right: ι-profiles in a configuration scan.

The technique for the dynamic scans [2] is necessary when the duration of the discharge is short and the corresponding induced electric fields are not negligible unless some compensation is provided. For example, the inclined line segment shown in fig. 1 (left) corresponds to the ι-profiles of fig. 1 (right), but a stationary plasma is obtained only for some 200 ms in the middle of the scan (thick line superimposed on the segment in fig. 1 left).

Figure 2 shows the time evolution of mode-number resolved frequencies detected with a set of Mirnov coils during several dynamic configuration scans like the one just described. There is a clear symmetry betwen downwards and upwards sweeping of the ι-profiles: in the first case (fig. 2 left), the m=4 mode associated to the resonance ι = n/m = 7/4 shows up first with high and then low frequency until disappearing. The m=3 mode is noticeable next with similar behaviour. In the upwards sweeping, the situation is inverted. In this case, an m=5 mode can also be detected. Note, despite several discharges with different densities being involved in the figure, that the frequency ratios agree quite nicely with the mode numbers ratio (e.g., high frequencies around 30, 40 and 50 kHz in fig. 2 –right– associated with m=3, 4 and 5 respectively). In fig. 2 we also plot the radial position of the vacuum resonances as a function of time, which informs approximately about the radial locations of the resonances that correspond to low and high frequency (i.e., plasma rotation) values.

Doppler reflectometry measurements at fixed different radial positions in the density gradient region of the plasma support the previous results. The peak of the main frequency due to density fluctuations is Doppler-shifted depending on the plasma rotation. Fig. 3 shows another case corresponding to a dynamic scan discharge (downwards ι-sweeping; see fig. 2 left): when the Mirnov coil frequency decreases at $t \approx 1115$ ms according to the spectrogram, the radial position of the 5/3 resonance in fig. 2 left is around $\rho = 0.85$ in normalized minor radius. The dip in the reflectometer signal in fig. 3 happens at approximately the same time when it is set to probe the region $\rho \approx 0.83$ and indicates that the 5/3 resonance is moving through that same radial location. Therefore, it is apparent that the resonance is accompanied by an independent rotation layer inmersed in the plasma. The fact that the rotation approaches zero in the case of fig. 3 is incidental. From several measurements of this kind we can conclude that there is a radial electric field in the region occupied by the resonance contributing always towards *positive*; in other words, if the ambient –in the absence of resonances– electric field is negative, it tends to zero or positive in the presence of the resonance; if the ambient field is positive, it strengthens [4].

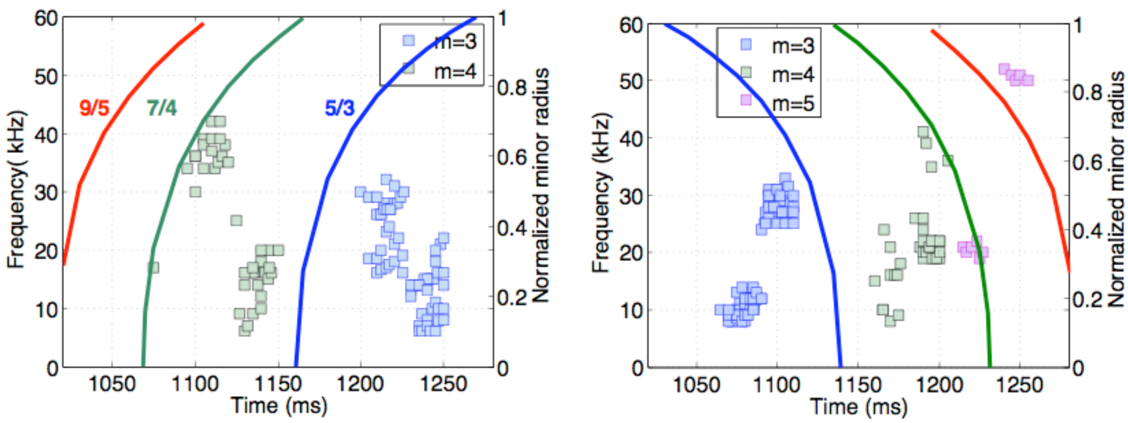

Figure 2. Frequencies and mode numbers resolved by the array of Mirnov coils in two dynamic configuration scans: downward (left) and upward sweeping (right).

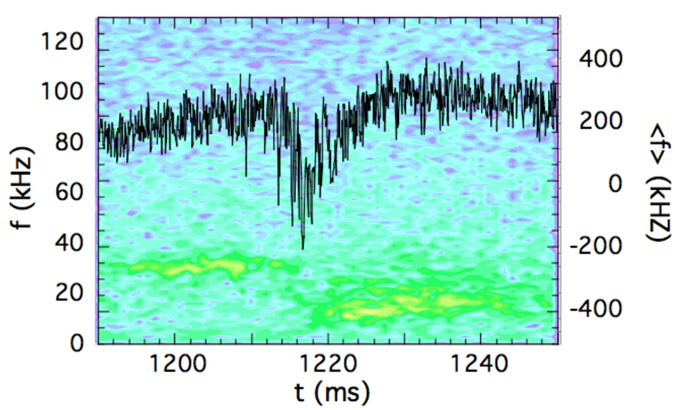

Figure 3. Frequency of Mirnov coil signal (left axis) and Doppler peak (right) for a dynamic configuration scan during the time at which the 5/3 resonance passes through the reflecting layer.

A dip like the one shown in fig. 3 can be seen also at outer radial positions with very little delay, suggesting that the resonances span practically the entire peripheral part of the plasma. Bolometry measurements taken with several arrays agree with these results about the frequency and extension of modes associated to the resonances. However, it is interesting to observe that such effects do not have a strong counterpart in profile flattening or any other "evident" incidence in the plasma profiles. Fig. 4 displays a set of emissivity profiles obtained in an upwards sweeping dynamic scan. Despite the proven fact that such resonances as 7/4 and 5/3 are crossing entirely the plasma, no clear footprint of their presence can be noticed.

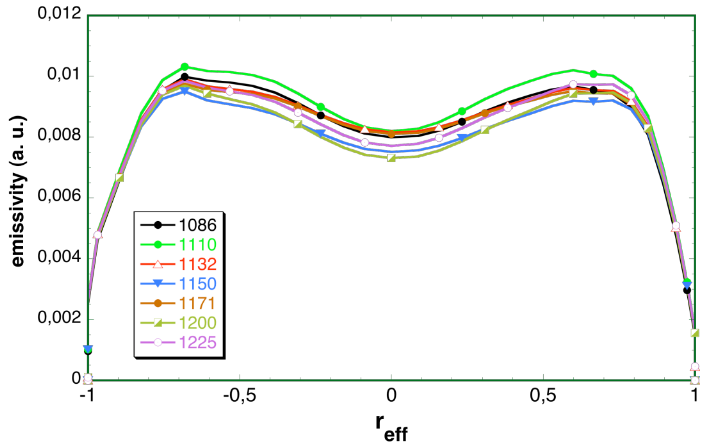

Figure 4. Reconstructed emissivity profiles from bolometer arrays during a dynamic scan discharge that makes the 5/3 and 7/4 resonances cross entirely the plasma during the times shown.

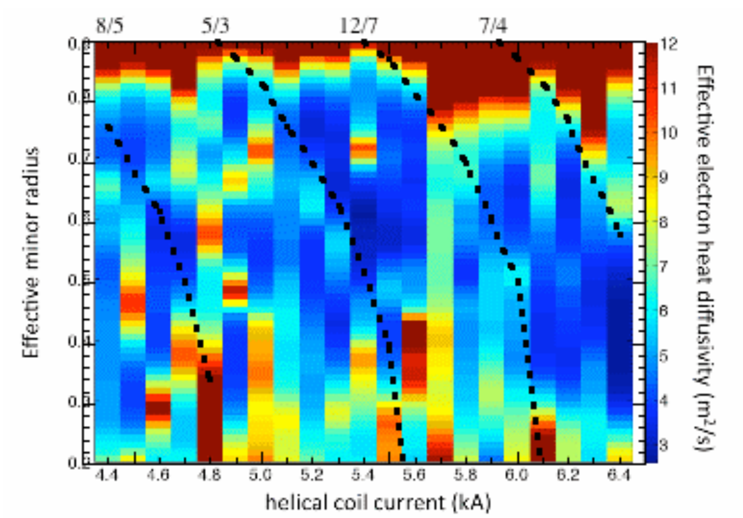

Figure 5. Effective electron thermal diffusivity profiles in a static rotational transform scan: each profile is an average obtained from Thomson Scattering density and electron temperature profiles for a fixed configuration. The radial location of the vacuum resonances is shown with dashed lines.

Other diagnostics have proven that there is, indeed, a subtle effect of the resonances on plasma profiles, particularly electron density and temperature. Fig. 5 is a map of effective electron thermal diffusivity profiles ($0.2 < \rho < 0.9$) obtained from averages of Thomson Scattering data for small sets (two to four discharges) of comparable discharges in static configuration scans [5,6] where the control parameter is I_{hx}; see vertical segment in fig. 1 left. After smoothing and averaging the density and temperature profiles obtained from the diagnostic –they are normally complemented with reflectometry and He-beam data for $\rho > 0.75$ –, a pattern of furrows and ridges can be tracked more or less coincident with the location of the vacuum resonances.

This kind of result has been pursued also with two types of dynamic scan: those previously described, where the ohmically induced currents are very small or negligible, thus changing little the magnetic shear; and with fixed configuration but ohmic induction, so the magnetic shear varies considerably [7]. In both cases the result is the same: there is a slight change in the plasma profiles that can be distinguished by plotting such sensible magnitudes as the gradient scale lengths (e.g., effective diffusivities). As an example, fig. 6 shows maps similar to the one in fig. 5 but for two dynamic scans: downwards (left) and upwards (right) sweepings. Albeit qualitative, one result from these figures is that there is an effect in plasma profiles that can be tracked in most of the bulk plasma as the resonances move through. Observe how the inversion of the dynamic scan also inverts the pattern of furrows and ridges. Unfortunately, the electron cyclotron diagnostic (ECE) used in this case to obtain the electron temperatures, and then the effective diffusivities, was not absolutely calibrated and there is no guarantee that the furrows correspond to the resonances. Another certainty from these results is that the rotational transform profile cannot be too different from the vacuum one –which yields the lines indicating the location of the resonances: from this we can draw an important conclusion: magnetic resonances like 5/3 or 7/4 can be set anywhere in the bulk plasma of the low magnetic shear TJ-II Heliac without causing a major damage to confinement (see also fig. 4). According to figures 5 and 6 one is tempted to conclude that there is even a benefitial effect because the location of the resonances seems coincident with lower values of the effective diffusivity. This would be congruent with the plasma behaviour during the dynamic configuration discharges, where the response of the plasma to a constant gas puffing sistematically consists of increasing the density when the main resonances, 5/3 and 7/4, locate around the density gradient region. On the other hand, there is still the doubt of whether there is some systematic effect of the superthermal electrons on both, Thomson Scattering and ECE diagnostics, that might be affecting somehow the measurements: it is known that high energy electrons get efficiently confined inside the magnetic islands [8], so their effect would follow the resonances as they move through the plasma in the configuration scans.

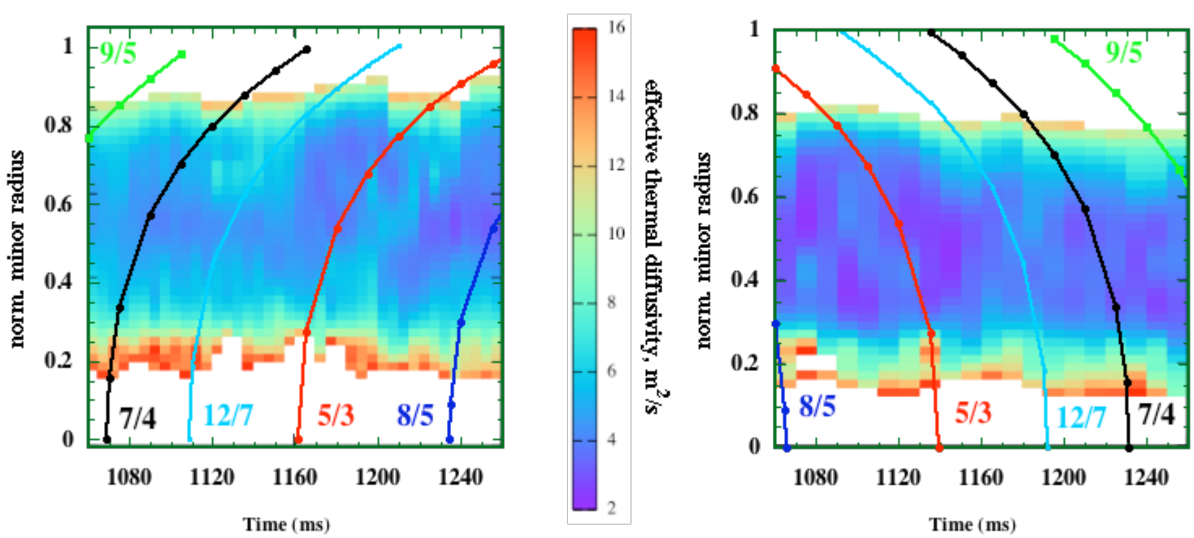

Figure 6. Effective electron thermal diffusivities obtained from ECE in downwards (left) and upwards (right) dynamic ι-scans. The location of vacuum magnetic resonances is indicated with lines labelled by the corresponding low order rational number.

Static and dynamic ι–scans have proven that, in the conditions of these plasmas, low order rational values of ι can be noticed throughout the plasma volume without deteriorating transport.

According to Thomson Scattering and ECE diagnostics, the effect is a subtle change in gradient lengths as can be seen by following the changes in effective diffusivities during the scans. Therefore, the effect can be seen in different conditions of collisionality (electrons: $\nu^* \approx$ 0.01–0.001) and magnetic shear (below $-(\rho/\iota)(\mathrm{d}\iota/\mathrm{d}\rho)=0.1$). In additon, several diagnostics show that there is a differential rotation of the plasma corona where the resonance is present, at least in the peripheral plasma region ($\rho > 0.75$), which clearly shows a local modification of the radial electric field. Something still to be proven is whether the resonances make steeper or flatter gradients, although the experiments so far point to the former.

Discussion

The results presented indicate that pure collisional and ExB shear dependent (e.g. electrostatic turbulence) contributions to transport should be considered together in presence of the magnetic resonances. If this is beyond the possibilities of realistic calculations, at least collisional transport calculations should include 3D effects. As long as the magnetic resonances do not destroy confinement, something proven here to be possible even in a low magnetic shear scenario, they can be seen as volume-filling structures between well formed magnetic surfaces, Ψ. In a stellarator, where the different mobility of electrons and ions obliges the exploration of flux surfaces $\mathrm{d}\Psi/\mathrm{d}t = \mathbf{v}_d \cdot \mathrm{grad}\,\Psi$ to be different among plasma species (here $\mathbf{v}_d$ represents the drifts due to magnetic spatial variations), magnetic resonances are quite likely to provoke localized sheared electric drifts and modify considerably both collisional and turbulent transport. Even though these notions have long been considered (see, e.g., [9]), their importance as effective confinement knobs in stellarators has been somehow dismissed.

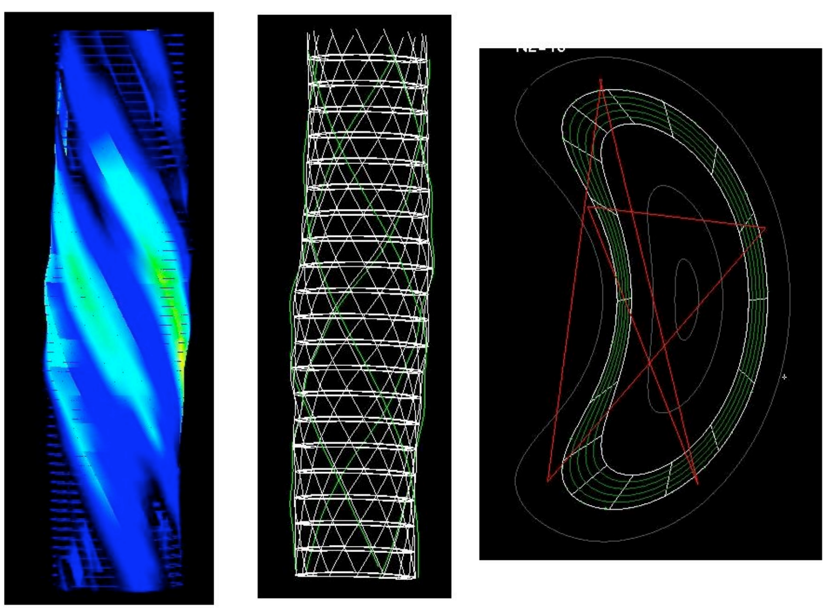

Figure 7. Kinetic calculation of the ion velocity distribution (left) using a mesh adapted to the geometry of a TJ-II magnetic configuration (center) that includes the 8/5 resonance in the shown (right) plasma corona. A similar3-D distribution is found for the plasma current density.

To help in quantifying the modification of collisional transport due to the magnetic resonances, we have started a program of calculations using a new drift-kinetic code based on the evolution of the electron and ion distribution functions in non-axisymmetric toroidal geometry –including TJ-II fields [10]. Fig. 7 is a calculation of the ion distribution function in the 3-D geometry of a TJ-II configuration that includes the resonance 8/5. The figure shows a straightened portion of the configuration for clarity. The structures shown correspond to the location and the helicity of the 8/5 resonance. A similar distribution but with opposite direction is found for the electron species, giving rise to a current density distribution that adapts to the vacuum magnetic islands. Given the value and direction of the current density and the magnetic field of the configuration, an order-of-magnitude estimate indicates that this current density would be able to heal the perturbation that gives rise to the islands. In any case, and since these calculations are preliminary and have been performed with the vacuum magnetic configuration, not including MHD feedback, we show them as an example of coupling between collisional transport and 3-D magnetic structure, which we pose as potentially important in the evaluation of transport in stellarator/heliotron devices for magnetic confinement fusion.

References

[1] T. Estrada et al., *L-H transition experiments in TJ-II*, these Proceedings I-23.

[2] J. A. Romero et al., *A flux control tool to perform single discharge magnetic configuration sweeping at the TJ-II Heliac*, 36th EPS Conf. on Plasma Physics, June 29 – July 3, 2009, Sofia, Bulgaria P4-183

[3] D. López-Bruna et al, Nucl. Fusion **49** (2009) 085016.

[4] O. Bondarenko et al., *Influence of low order rational surfaces on the radial electric field of TJ-II ECH plasmas*, these Proceedings P02-20

[5] V. I. Vargas et al., Nucl. Fusion **47** (2007) 1367–75

[6] D. López-Bruna et al., *Modification of transport due to low order rationals of the rotational transform in ECH plasmas of the TJ-II Heliac*, Proc. 16th ISHW, Toki, Gifu, October 15--19, 2007, P1-016

[7] D. López-Bruna et al., Europhys. Lett. **82** (2008) 65002

[8] F. Medina et al., Rev. Sci. Instr. **72** (2000) 471

[9] N. V. Ivanov, A. B. Pimenov, P. P. Khvostenko, Sov. J. Plasma Phys. **10**, 253 (1984)

[10] J. M. Reynolds et al., *A new code for collisional drift kinetic equation solving*, AIP Conf. Proc. – November 2, 2008 – Volume 1071, pp. 72-81