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Effect of magnetic resonances in the effective electron heat transport of TJ-II ECH plasmas

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Introduction

The TJ-II Heliac [1] is a high rotational transform ($\iota\!\!\!-$) low magnetic shear device for magnetic confinement fusion studies. The low density discharges ($\lesssim 10^{19}$ m^{-3}) started and maintained by Electron Resonance Heating (ECH) display increased electron temperature gradients at the location where low order rational values of $\iota\!\!\!-$ (magnetic resonances, in short), as found after analyzing a fine $\iota\!\!\!-$ scan of ECH plasmas based on Thomson Scattering data [2]. Differences between the $\iota\!\!\!-$ in vacuum and in the presence of the plasma can come from internal currents. A way to overcome this uncertainty is studying discharges with induced currents much larger than the bootstrap one. In this way, the changes in electron temperature (T_e) gradients can be confidently related to the moving position of the magnetic resonances.

The interest on the effect of magnetic resonances in the transport properties of stellarator plasmas is not new. It is an experimental fact that they can deteriorate transport [3] and, actually, the two main branches in Stellarator/Heliotron devices can be separated by their different approaches to overcome this problem: either magnetic resonances are permitted in the plasma with a high magnetic shear, or they are avoided keeping the $\iota\!\!\!-$-profile in magnetic resonance free regions, which requires low magnetic shear. Both approaches have their advantages and drawbacks. However, if there are general conditions under which the presence of such resonances does not deteriorate transport to a worrisome level, the design of a stellarator reactor may benefit from more freedom to optimize equilibrium against β or neoclassical transport properties. The present results point in this direction.

Experiments

The experimental data come from time resolved diagnostics like Electron Cyclotron Emission, Soft X-Ray chords and interferometers. The plasmas are generated and sustained by 300 kW of nominal Electron Cyclotron Heating power (ECH) and have densities in the range $0.5-0.7\times10^{19}$ m^{-3}. Typical internal currents are ~ 0.5 kA in the absence of Ohmic induction. The plasma average minor radius is close to 20 cm and the plasma volume is ≈ 1 m^3. Plasma currents are induced with the help of the OH transformer, which provides small loop voltages ($\lesssim$ 1 V) almost independently of the magnetic flux surface. The vacuum magnetic configuration is the same for all the discharges here presented, with the ι-profile slightly above the resonance 3/2. The induction process changes ι as the calculation of Fig. 1 illustrates. From this evoluton we obtain the path followed in minor radius by each resonance as the OH-induced toroidal plasma current is varied in time. Fig. 1 corresponds to a discharge with double ramp in the OH coils, i.e., the induced voltage changes sign at a certain time in the plasma boundary. In consequence, ι is quite flat and close to the resonance 8/5 when $t \approx 1140$ ms. In other experiments we have worked with single ramps to impose positive or negative induction alone. The evolution of the plasma current and the power-balance transport analysis has been done with the ASTRA package [4]. We obtain effective electron heat diffusivity profiles, $\chi_e \sim Q/(n_e T_e')$, where Q is the ECH power deposited up to the radial position of the corresponding χ_e value, n_e is the electron density and the prime means derivative with respect to the "radial" coordiante ρ.

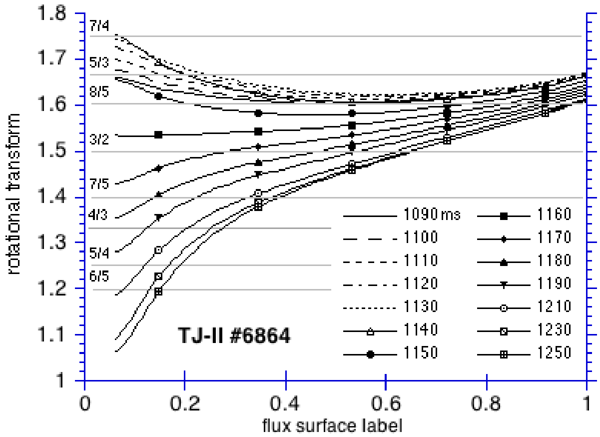

Figure 1: Calculated evolution of ι in a discharge with double OH ramp and net plasma current peaking at $t = 1135$ ms. Downward moving ι-profiles are drawn with markers.

Results

Fig. 2 shows the evolution of χ_e profiles for the discharge corresponding to Fig. 1. At $t \approx 1140$ ms $\iota(\rho,t)$ is being bent downwards by the penetration of negative induced current densities and there is a large radial region with $\iota \approx 8/5$. Near this time, the experiment shows some flattening of the T_e-profile in the region $0.5 \lesssim \rho \lesssim 0.7$, which implies a transiently larger χ_e. This is a known effect in TJ-II discharges with positive –i.e., plasma current increasing– ohmic induction [5]. Observe also in Fig. 1 that the minimum of ι locates near $\rho = 0.5$ and only very slightly above 8/5. If the electron temperature is a little bit higher than estimated (so the current penetrates more slowly) or the bootstrap current is such that it lowers ι by a small amount (a mere 2%) around $\rho = 0.5$, then one or two roots of $\iota(\rho) = 8/5$ occupy the region $0.4 \lesssim \rho \lesssim 0.6$ for all times $t \lesssim 1140$ ms. This is indicated in figure 2 with a short dashed line connecting the 8/5 lines. Afterwards, the induced currents are larger and so is the magnetic shear, which helps in determining the radial position of each resonance. We note that the moving local minima of χ_e draw furrows in the contour map that are credibly related with the paths of the resonances showing up and displacing in minor radius as the magnitude of the plasma current increases. In particular, the most important resonance (3/2) moves from the core to $\rho = 0.65$ according to the calculations in Fig. 1. In the region $0.4 \lesssim \rho \lesssim 0.7$, this resonance is coincident with the minima of the corresponding χ_e profiles. The 7/5 resonance can be associated with the local minimum at $t = 1250$ ms, $\rho \approx 0.38$.

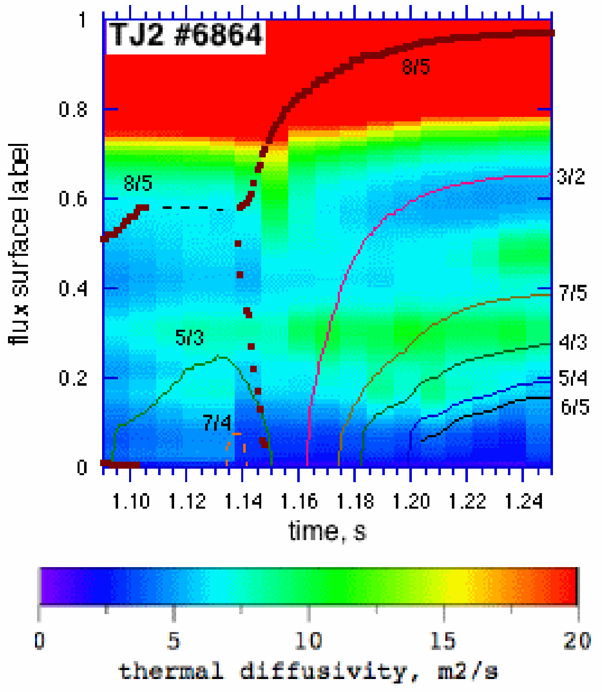

Figure 2: Contour map of $\chi_e(\rho,t)$ for TJ-II discharge #6864 with double OH ramp. The path of several calculated resonances is shown with lines. The dashed line connecting the branches of the 8/5 resonance represents the position of the calculated minimum of ι (see Fig. 1), which has a value by 2% above 8/5.

The next two discharges are characterized for having single OH ramps, positive –iota increases– in the case of Fig. 3 (left) for shot #7036; and negative in Fig. 3 (right) for shot #7046. The colour scale is identical to that of Fig. 2. The paths followed in the maps by several resonances is drawn with lines. An increment in χ_e at $t \approx 1120$ ms is found in shot #7036 coincident with the moment in which ι has a minimum near $\rho = 0.5$. Let us remember that TJ-II vacuum ι-profiles have slightly negative magnetic shear, so during the first stages of positive induction ι bends due to increasing values in the core region. This causes zero magnetic shear near the minimum, possibly in an extended region. The effect is transient due to the time evolution of the current density profile and the temperature gradients –seen through χ_e in these plots– recover afterwards. Then, the region of smaller χ_e can be seen to move towards the edge in rough coincidence with the location of the 5/3 resonance. Later in the discharge, $t \gtrsim 1200$ ms, the lower values of χ_e are coincident with the calculated location of the 7/4 resonance. Discharge #7046 is a similar plasma except for the sign of the induction. Here, the sign of the magnetic shear is always negative and, consequently, there is no minimum of ι inside the plasma. No transiently larger χ_e similar to the previous two cases is found. However, a furrow of low diffusivity can be identified approximately coincident with the calculated location of the 3/2 resonance, which is qualitatively the same effect shown in the previous figures. In consequence, if the lowering of the effective thermal diffusivity χ_e is due to the presence of the resonances, we conclude that it does not depend on the sign of the

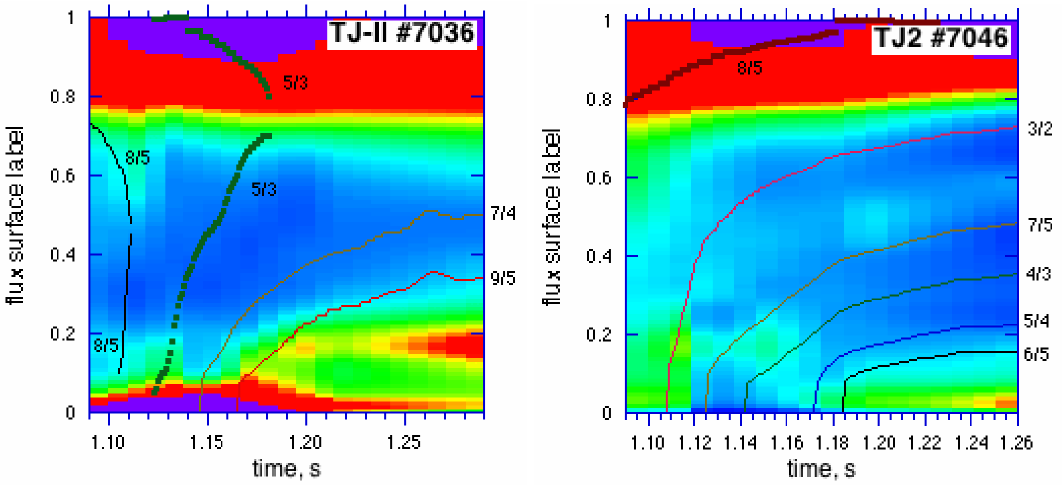

Figure 3: Same as Fig. 2 for discharges #7036 (left, positive induction) and #7046 (right, negative induction).

magnetic shear. Furthermore, the χ_e map shows other minima closer to the core, possibly related to the presence of another important resonances, 7/5 and 4/3. The closer we get to the plasma core the less valid is the analysis because χ_e is affected by the shape of the ECH deposition profile, here approximated by a centered Gaussian, and the internal currents can be affecting much more the ι-profile. These experiments [6] together with those in steady-state discharges [2] support the notion that electron heat transport is *retained* where there is a low order rational value of the rotational transform, even in conditions of small magnetic shear.

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