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Evolution of rotational transform in ECRH discharges with induced current in TJ-II

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INTRODUCTION

A new line of experiments with the TJ-II device [1] was opened during the 2001 campaign to explore the effect of induced moderated ohmic currents on confinement [2]. Up to date, all the results pertain to electron cyclotron resonance heated plasmas without density feedback control and show a rather reproducible and systematic response of the plasma to the induction process. In brief, the confinement improves with negative induced currents and vice-versa, although high enough plasma currents (~7 kA) of either sign seem to always benefit the confinement. Such results may be of interest for the physics of hybrid concepts, where moderate plasma currents (~ 50 kA) allow for a combination of stability at high pressure, good transport properties and compactness (see e. g. [3]). In the case of TJ-II, it is known that the plasma is responding directly to the induced current rather than to the induced electric field [4]. The very flat vacuum rotational transform, $\iota/2\pi$, of typical magnetic configurations in TJ-II (like those corresponding to these experiments) suggests that the global magnetic shear is playing some role on transport. At the same time, the presence of low order rational flux surfaces should have a recognizable impact during the ohmic induction, although neither it is clear how such rational values of $\iota/2\pi$ affect plasma confinement, nor it seems to be the only element at play. For these reasons, we have calculated the evolution of $\iota/2\pi$ in discharges with induced plasma currents. Here we take advantage of the fact that the net bootstrap current is considerably smaller than the ohmic one. A detailed knowledge of how the rotational transform evolves in these discharges is necessary to identify (i) the effect of low order rationals seen by several plasma diagnostics and (ii) other effects apparently uncorrelated with the presence and evolution of such low order rational flux surfaces during discharges.

EXPERIMENTS WITH OHMIC INDUCTION

TJ-II plasmas with ohmic induction have been obtained with some less than 300 kW of electron cyclotron heating (ECH). Four horizontal coils (OH coils) are used to induce positive and negative plasma currents up to 10 kA with negligible heating power. The particle source from the gas-puffing valves is set to allow reference discharges (no induction) with densities around $0.5 \cdot 10^{19}$ m^{-3}, although it cannot be guaranteed that particles from recycling processes at the vacuum chamber wall will stay the same under the evolution of the plasmas with ohmic induction; and maximum temperatures around 1 keV.

An important magnitude to be diagnosed is the plasma loop voltage –the circulation of the induced electric field along a sufficiently long path following a magnetic field line with non-rational rotational transform. Of course, the loop voltage diagnostic in the TJ-II device referres to a well defined, albeit different, circuit: it measures the induced voltage in a circuit similar to the central conductor around which the whole plasma rotates in four periods. Therefore, the diagnostic and the required plasma loop voltage may be different. Several calculations using the real geommetry of the OH coils, the central conductor and considering vacuum configurations of TJ-II show that the loop voltages defined as above coincide up to well below 1% for any vacuum magnetic surface if only the variation of currents in the OH coils is taken into account. Therefore, it is expected that the plasma loop voltage in, for example, the last closed magnetic surface and the loop voltage from the diagnostic be the same during the constant OH coil current ramp once the plasma current has reached steady state. Finally, the total plasma current is used as a boundary condition for estimating the evolution of the plasma current density. This evolution is calculated imposing the experimental evolution of electron density and temperature in an approximated geommetry. It has been checked that the flux-surface averaged metric that we are using is accurate enough for our present purposes. We assume that the parallel conductivity responds to Spitzer formula with a simple correction due to the fraction f_t of trapped particles, $\sigma_{\parallel} = A\sigma_{SP}$ $(1-f_t)$, with a global factor A that we adjust to match the calculated loop voltage and the diagnosed one.

RESULTS AND CONCLUSION

Fig. 1 shows the results of a calculation for TJ-II discharge #7045 with negative induction. This discharge has a low plasma line density and low contribution from bootstrap current, which is suited for estimating a value for *A*. The results of Fig. 1 are obtained with $A = 0.8$, indicating the appropriateness of using σ_{SP} for TJ-II ECH plasmas. Also shown is the value of the rotational transform at the magnetic axis, $\iota(0)/2\pi$.

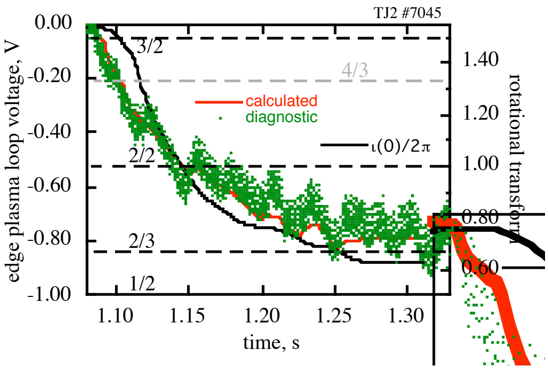

Fig. 1. Comparison between calculated –at the plasma edge- loop voltage (light line) and loop voltage diagnostic (dots) for a discharge with induced ohmic current. The corresponding evolution of the magnetic axis rotational transform is drawn with a black line. Lowest order rational values within the range are shown with dashed lines.

As expected, several plasma diagnostics display effects easily associated with $\iota(0)/2\pi$ crossing the main low order rationals. This can be appreciated in Fig. 2, where the time traces of the central electron temperature and soft X-ray emission, line averaged density, temperature at half effective minor radius and net plasma current are shown for the same discharge #7045 of Fig. 1. Thus, there is an abrupt change in $T_e(0)$ accompanied with increments in other magnitudes a few milliseconds after the 3/2 rational is calculated to show up. Note that the plasma conductivity is quite sensitive to electron temperature and plasma current distribution. A small positive bootstrap current in the core region can easily account for the delay observed between calculation and experimental time traces. Likewise, $\iota(0)/2\pi$ reaches the value 1 at t = 1145 ms and 2/3 at t = 1254 ms. It is interesting to observe in Fig. 1 that the 2/3 rational stays in the magnetic axis region coincident with the activity in the central temperature channels. Such activity could not be observed with the previous rationals possibly due to the fast sweeping of $\iota(0)/2\pi$ values. We also observe the known effect of sudden increments in the central electron temperature channels, which we adscribe to the presence of the low order rational in the region of power deposition [5], but no major effects are seen on confinement trends except for a slight and steady improvement.

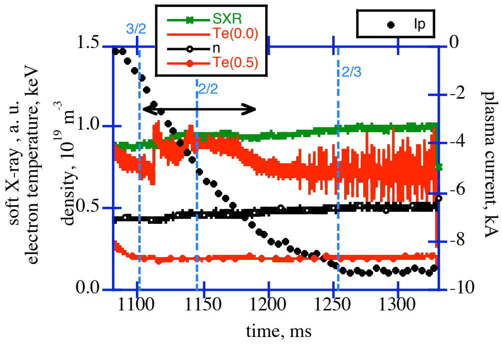

Fig. 2. Time traces of soft X-ray emission from the plasma core (line with crosses), central T_e (line), line averaged density (line with dots), T_e at half minor radius (line with diamonds) and net plasma current for a discharge with negative induction.

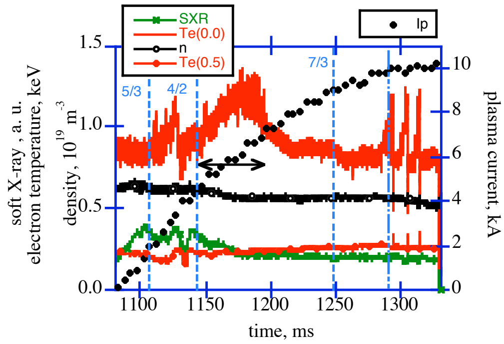

Fig. 3. Same as Fig. 2 for a discharge with positive induction. From left to right, vertical dashed lines indicate the appearance of low order rationals –see labels- in the core. The last vertical line indicates the time at which $\iota(0)/2\pi = 2.42$.

During the time indicated by the double arrow, the $\iota(0)/2\pi = 1$ flux surface is moving outwards through the ECH deposition zone (same in Fig. 3).

If we are to look for the mere presence of rationals within the plasma as an explanation for the effects reported on confinement [4], then something similar should be found with positive induction. The discharge in Fig. 3 shows degradation of plasma parameters with positive current: the effect of low order rationals entering the plasma from the magnetic axis can be identified as with negative currents, but the general trends (in line density and soft X-rays, for example) are opposite to what is found with negative induction. Here, $\iota(0)/2\pi = 2.42$ –close to the 5/2 value- at times above 1190 ms but there is no further increment. Again, a small positive bootstrap currentat the core may explain the disagreement.

In summary, there is an ongoing work for analysing discharges with ohmic induction in TJ-II. First results indicate that the presence of lowest order rational values of $\iota(0)/2\pi$ is easily identified, but the response of the plasma seems to be obeying to something else. Further work is aimed at separating direct effects due to the presence of islands from other possible effects, like the influence of global magnetic shear on transport.

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