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Effects of magnetic shear on confinement in TJ-II ECRH discharges

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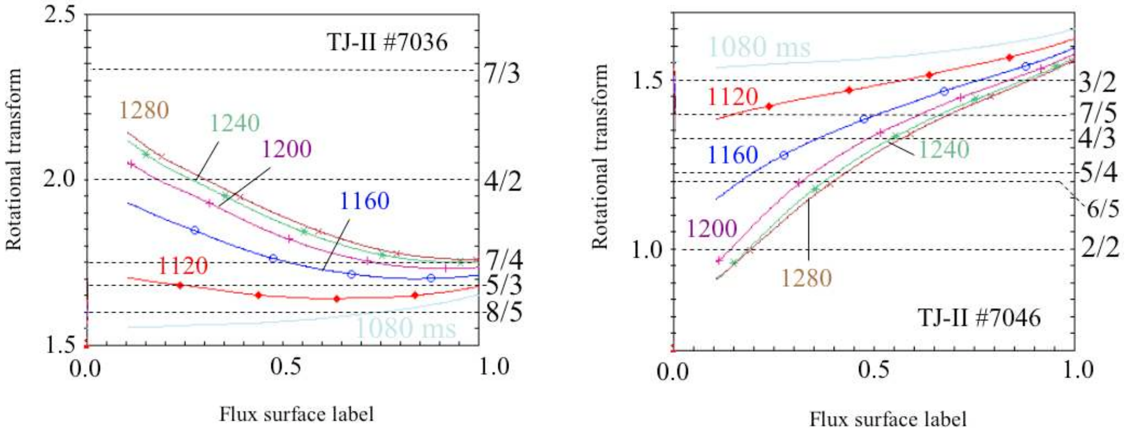
Introduction

Stellarators with very low magnetic shear are supposed to allow for good confining properties because low order rationals in the rotational transform $\iota/2\pi$ can be avoided throughout the plasma. For this reason, the modification of the ι-profile via bootstrap current and its possible control has been a matter of research in low shear machines like the W7-AS stellarator [1]. At the same time, these confinement devices are well suited to study the evolution of the rotational transform and its shear as long as bootstrap currents can be ruled out. This is the case in electron cyclotron resonance heated (ECRH) discharges in TJ-II [2] with moderate (negligible modification of the magnetic field strength) ohmic induction. Such discharges show a dependence of confinement on the sign and strength of the induced plasma current. Since the magnetic shear in vacuum TJ-II magnetic configurations is very small, positive (negative) induction forces positive (negative) magnetic shear. In this work we perform interpretative transport analysis on ECRH discharges with ohmic induction to show the experimental relationship between magnetic shear and transport.

Experimental data

Discharges with ohmic induction in TJ-II must be analyzed in an evolving state because the time scale of the evolution of the plasma current is comparable to the duration of the discharge itself. Therefore, some experimental magnitudes must be followed during the discharge to do transport analysis. The minimum set of experimental data necessary consists of the electron and ion density and temperature profiles and the net plasma current (a boundary condition to calculate the evolution of the rotational transform). We assume constant source profiles for heat and transport during a discharge, which is a good assumption in the case of the ECRH but a questionable one in the case of the particle source due to the plasma-wall interaction. Total radiation loss profiles are roughly shaped according to the density profiles suggesting that the effective charge is quite homogeneous. We consider the transport analysis to be significant only in the bulk region, which we extend at most from approximately $\rho = 0.1$ to $\rho = 0.8$, because the region around the magnetic axis is affected by ECRH pump out mechanisms and in the edge region we expect large losses due to the magnetic ripple. Therefore, our analysis concentrates on diffusion.

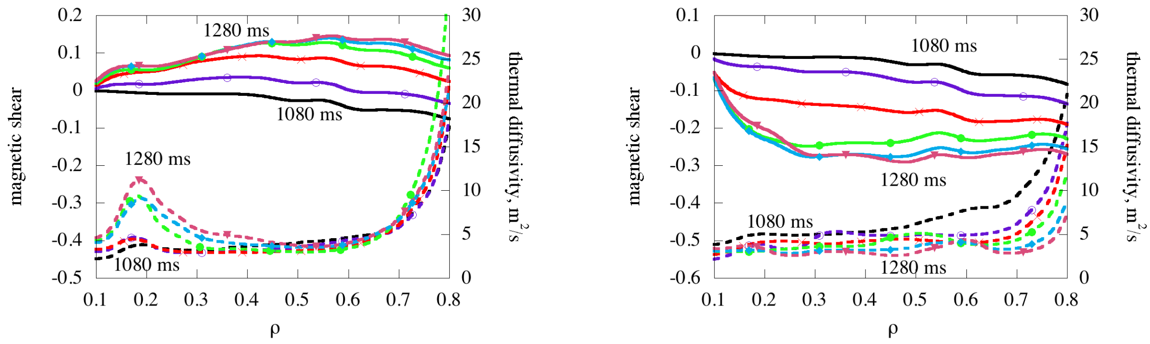


(a) (b)

Figure 1: Evolution of the rotational transform in ECRH TJ-II discharges #7036 (a) and #7046 (b) under positive and negative ohmic induction respectively.

The evolution of the electron temperature, T_e, is obtained with the electron cyclotron emission diagnostic (ECE), which could be compared with Thomson Scattering data when available. The evolution of T_e is also used, together with several chords of soft X-ray emission, to obtain the evolution of the electron density profile. In the case of the net plasma current we use the Rogowski coil and complement this information with the loop voltage diagnostic. A relevant information that we have checked numerically is that, in steady state conditions, the plasma loop voltage induced by the transformer coils in the magnetic axis coincides by design with the loop voltage of the diagnostic. In addition, the voltage per toroidal turn obtained following a sufficiently long circuit along a magnetic field line in TJ-II is quite approximately the same for any flux surface in vacuum. Therefore, we know from the experiments the evolution of the net plasma current and the plasma loop voltage, which permits a fair validation of the formulas we use for the plasma resistivity: Spitzer's expression corrected with the fraction of passing particles. Finally, we have performed calculations of the modification of the rotational transform with several profiles of plausible bootstrap current density profiles giving net currents as in the experiments without induction. It is found that such modifications are small in comparison with transformer induced currents, a reason why our analysis does not include any model for bootstrap currents but only the induced ones.

Fig. 1 shows the evolution of $\iota/2\pi$ in ECRH discharges under positive (a) and negative (b) induction at several times during the discharge. Net experimental plasma currents change from near zero to +10 kA (a) and -10 kA (b). These calculations use the flux surface averages of the metrics for the magnetic configuration. We can see that several low order rational values of $\iota/2\pi$



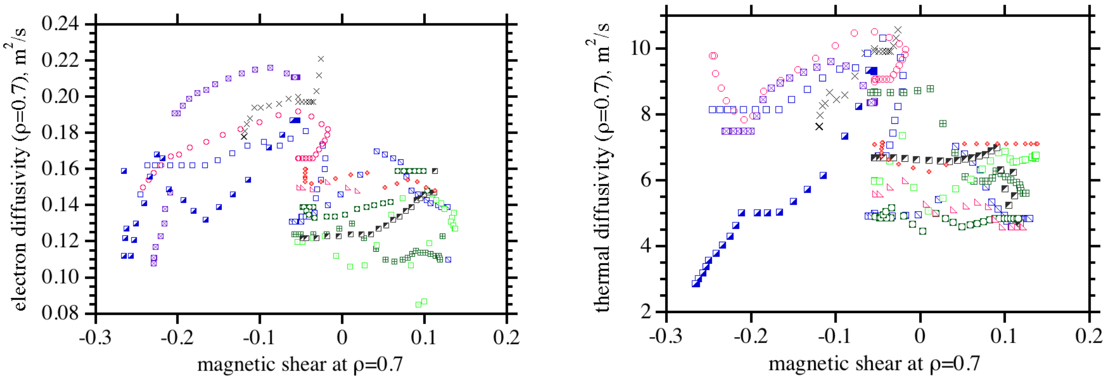
(a) (b)

Figure 2: Evolution of the magnetic shear in ECRH TJ-II discharges #7036 (a) and #7046 (b) under positive and negative ohmic induction respectively (see Fig. 1).

are clearly crossed, some of them moving completely throughout the plasma. Some diagnostics, like the Mirnov coils or the ECE, respond to the appearance of lowest order rationals near the edge or in the plasma core. It must be mentioned, however, that these signatures of low order rationals seem to almost disappear with little magnetic shear.

Magnetic shear and confinement

It is a known fact that positive and negative induction in TJ-II work in opposite ways in terms of confinement: in the first case, confinement degrades while it improves in the second. Exceptionally, net induced plasma currents above some 7 kA seem to recover confinement [3]. At the same time, Fig. 1 clearly indicates that low order rationals move through the plasma in both cases. This is one of the main reasons for us to turn to investigate other magnitudes, like the magnetic shear, defined here in the usual way $\hat{s} = -(\rho/\iota)(d\iota/d\rho)$ in every flux surface ρ. Fig. 2 shows the evolution of $\hat{s}$ that corresponds to Fig. 1. In the case of positive induction the shear reaches positive values slightly above 0.1; and in the cases of negative induction, magnitudes close to 0.3 (but with opposite sign) are reached. Nevertheless, the effect of $\hat{s}$ on the thermal diffusivity χ_e looks gradual in both cases. In the case of positive shear we find little change in χ_e except for a small peak that develops near the core. This is not a systematic feature of these discharges and, in fact, even though the peak increases with larger positive shear, the effect on confinement is negligible because it only affects a small region in the core. Local particle transport is difficult to asses because we do not know the distribution of neutrals inside the plasma. At the same time, the density gradients evolve in an opposite way with positive (flatter) and negative (steeper) net induced currents. Assuming, as mentioned at the beginning, a fixed particle source, we can make a representation of difussivities (not shown) from which the same information is obtained for negative shear (diffusivities decrease for $\rho \gtrsim 0.7$). On the



(a) (b)

Figure 3: Particle (a) and thermal diffusivities (b) and the calculated magnetic shear at $\rho = 0.7$ for a set of TJ-II ECRH discharges. Each symbol corresponds to one discharge.

other hand, we find an increment of particle diffusivities with positive shear, which explains the worsening of confinement on discharges with positive ohmic current in TJ-II. In summary, we find that heat and particle transport and magnetic shear are related to shear in a somewhat different manner: positive shear increases particle transport while heat transport seems to be less affected or increases with shear. On the other hand, negative shear systematically decreases particle diffusivities while heat transport remains roughly the same or, if any, diminishes giving rise to an overall enhancement of confinement. Fig. 3 summarizes these results showing the local ($\rho = 0.7$) relationship between the calculated values of magnetic shear and thermal (a) and particle (b) diffusivities. Negative shear correlates with lower transport the larger the magnitude. Positive shear up to approximately $\hat{s} = 0.05$ tends, although less markedly, to increase transport coefficients. Larger plasma currents (or larger values of $\hat{s}$) can invert trends as mentioned above. Finally, it must be warned that in Fig. 3 we gather experiments with ohmic induction in ECRH plasmas without any other sort of grouping. Therefore, the values of the transport coefficients can be compared in a single discharge (one symbol) but not necessarily among different discharges (e.g. confinement improves with density in TJ-II ECRH plasmas [4]).

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