Studies of Electron Transport and Current Diffusion in Switched ECCD experiments on TCV

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ABSTRACT The aim of the present work is to provide a better insight on the magnetic shear profile modification in the Switched ECCD experiments. Modelling of the plasma current density is carried on by the ASTRA transport code employed in both predictive and interpretative modes, with two shear-dependent models for the calculation of the electron energy diffusion coefficient. In this context, the modulation of ECCD is the only actuator for the transport properties modifications. This study confirms the synergy between electron transport and magnetic shear, both of which are modulated around the EC deposition region. It also allows to completely decouple the effects of the current profile modification from those of slight plasma heating misbalance or non-constant plasma elongation, which are key concepts at the basis of Switched ECCD and can be a rather delicate experimental issue. The numerical results moreover validate a previous rough model based on electrodynamics calculations.

Understanding the physical connection behind electron confinement and plasma current density profile has become of primary importance for the most successful exploitation of a future fusion reactor. These two quantities were found to be strongly related by a variety of dedicated experiments in many tokamaks. In the Tokamak à Configuration Variable (TCV) it was shown that the electron confinement improves by modifying the steady-state current density from peaked to hollow [1] and such behaviour is believed to be due to the suppression of plasma turbulence in the presence of a negative magnetic shear and a finite Shafranov shift [2]. TCV Electron Cyclotron Resonance (ECR) system is equipped with two independently supplied clusters each composed of 3 X2 gyrotrons, providing up to 3 MW of total ECR power. This allows generation of a Switched EC Current Drive (SECCD) [3] in L-mode plasmas, i.e. driving alternatively positive or negative local ECCD at constant total input EC power during a single discharge. The EC beams are injected, alternatively, at a constant frequency inside the plasma, maintaining symmetric aiming of the beams and the same power deposition profile. For each SECCD discharge a preliminary ECH shot has been performed, with alternated on/off phases of the two clusters, to check that the total plasma energy stays constant. If not, the P_{ECH} is adjusted to make it so. The idea underlying these experiments is indeed to decouple the contributions of specific heating oscillations from those of the current density tailoring, so that any modification in the transport properties of the plasma is to be ascribed only to the shear profile $s(\rho)$ modulation realized by the ECCD switching. Modelling of the current density profile is thus necessary, there being no direct measurement available at TCV. This is carried on with the ASTRA [4] code for transport analysis, for three different cases: a) in interpretative mode, by providing the measured electron temperature profile, $T_e(\rho, t)$, as an input; b) in predictive mode, with the Rebut-Lallia-Watkins (RLW) semi-empirical local transport model [6] to evaluate the electron energy diffusion coefficient χ_e, which is proportional to $|1/s|$; c) in predictive mode again, using the model b) multiplied by s^2, just to compare the effect on T_e with a model having χ_e~ s. The present analysis refers to shot #24867 of Ref. 3 and the two free parameters involved in the models were chosen to adequately reproduce the measured $T_e(\rho)$ for the corresponding ECH discharge. The plasma response has thus been studied in presence of SECCD to understand the differences in time scales and transient behaviours between the various models employed and with different experimental conditions, such as changes in period and deposition location. This analysis does not aim to correctly calculate the plasma current diffusion reproducing the exact experimental set-up, because of the complexity of the dynamics associated with the SECCD discharges. In the simulations presented here only a few parameters (I_{ECCD}, $T_e(\rho)$) have been varied each time, the others (κ, δ, $P_{ECH}(\rho)$, $n_e(\rho)$, $T_i(\rho)$, I_p) being fixed, which is often difficult to realize experimentally. The two T_e profiles used correspond to measured average profiles of each phase (co-/cnt-SECCD). Fig. 1 shows the calculated time traces of the various plasma current components and central T_e, due only to modulation of I_{ECCD} at fixed, constant T_e. The total modulation period is 200 ms, as in the experiments, and is found not to be long enough for a steady-state to be reached, as the simulated parallel electric field is not yet relaxed. Simulations with much longer modulation times have been done, identifying the modulation frequency for steady-state to be around 3 times larger than the experimental one. During the transition from one phase to the other, I_{ECCD} is imposed to rise between its minimum/maximum values within 30 ms; then it is held constant. Figs. 2 and 3 compare the shear modulation, which reaches its maximum at the deposition location ρ_{dep}=0.22, for the two interpretative runs at fixed and varying $T_e(\rho)$, respectively. One sees

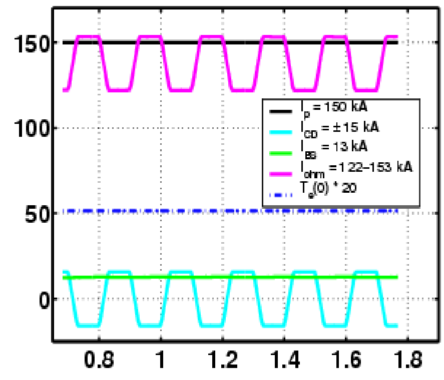

Fig. 1 t [s]

that the shear behaviour is essentially the same in both cases, with Δs ~ 0.4 at ρ_{dep}. The latter case can be compared with previous, rough modelling based on electrodynamics calculations, discussed in Ref. 3. The main results of such modelling are that, in the deposition region, s passes from 0.2 to 0.7 while switching from the co- to cnt-phase, while the q = 1 surface stays in the plasma and $q(\rho_{dep})$ oscillates between respectively 1.2 and 1.4. The j_{ECCD} used in most of the rough modelling was determined by the linear Toray-GA code, while for the present calculations the modulated co- and cnt-SECCD are calculated by solving the Fokker-Planck equation including radial particle diffusion, resulting in a profile slightly broader than the one predicted by linear theory. Nevertheless, the two models show similar relative changes in the shear modulation.

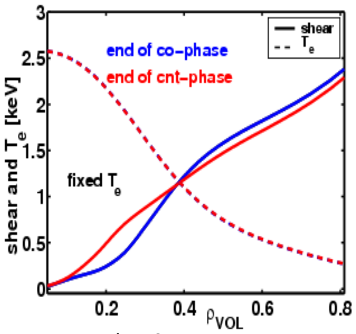

Fig. 2

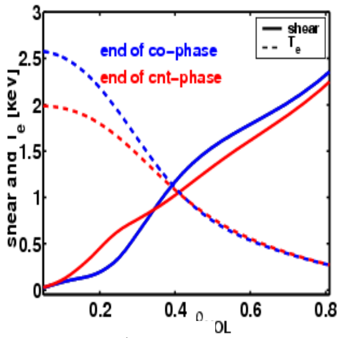

Fig. 3

Concerning the simulations involving χ_e models (cases b and c), the location and extent of the shear modulation is in good agreement with the interpretative results above, as evident from Figs. 4 and 5.

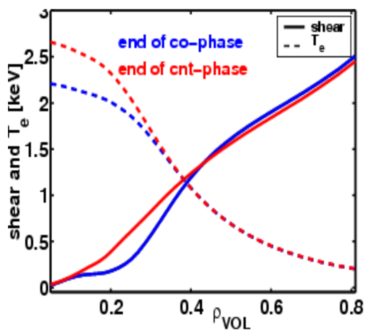

Fig. 4

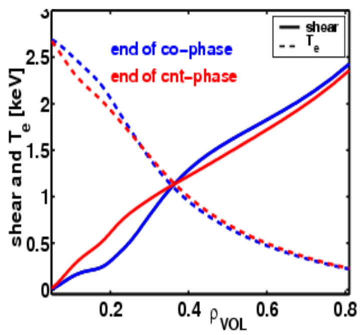

Fig. 5

This confirms the robustness of the shear modelling. For the RLW model (case b, Fig. 4), however, the calculated T_e profiles are 180° out of phase with the experimental data (Fig. 3). In the simulation, the higher central T_e corresponds to the end of the cnt-phase, where the magnetic shear is higher. This can be explained by the inverse dependence of the model on the shear. The linear shear-dependent model, instead, predicts a slightly higher T_e for $\rho <$ 0.25, more in accord with the experiments.

Gyrokinetic linear simulations [2] have shown that confinement properties increase if the shear decreases, in the radial region where s < 1. At larger values of s (typically s > 1-1.5), the opposite behaviour is predicted so that one could experimentally investigate transport properties at larger s by shifting the SECCD deposition location more off-axis, and see if in this case the maximum T_e is obtained in the cnt-ECCD phase. The radial deposition of the ECH power has been changed to ρ_{dep} = 0.5 (Fig. 6) to study the range of shear modulation accessible at such radius. By driving a maximum I_{SECCD} of about 10 kA, peaked at the new ρ_{dep}, s spans from 1.4 to 1.65 (Fig. 7) and, if I_{SECCD} increases to 17 kA, s ranges 1.3-1.7.

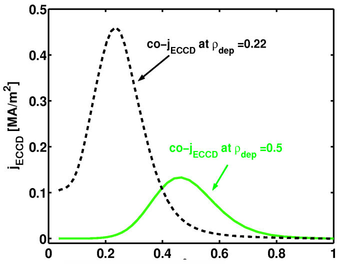

Fig. 6

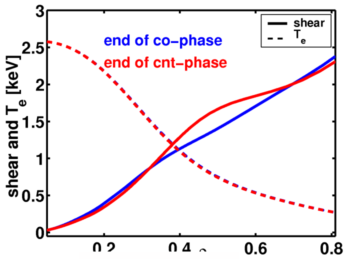

Fig. 7

A more recent series of SECCD discharges with double the ECH power (i.e. 2+2 gyrotrons) and feedback control on the plasma elongation was realized with the purpose to create a large database featuring different values of the plasma current, radial location and width of the deposited power. Unfortunately these discharges exhibit constant MHD activity, which complicates the correct interpretation of the observed electron temperature modulation. One clearly observes that the mode activity is very intense during all co-SECCD phases and fades out when switching to cnt-SECCD, as seen in the spectrogram of Fig. 8. This confirms experimentally that the q profile is being modified locally, but may also explain the fact that no significant effect on T_e is observed in these new discharges. Nevertheless, the identification of the toroidal and poloidal mode numbers for these modes should allow a possible validation of the ASTRA modelling by comparison with the simulated rational q surfaces. Such work could also be used to aid in avoiding MHD modes and thus in designing future SECCD experiments.

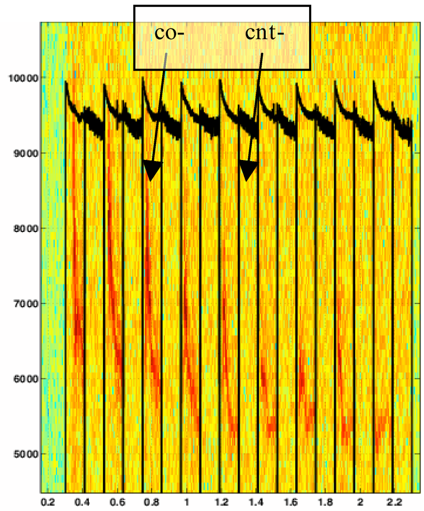

Fig. 8 t [s]

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