# 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. Indeed, these two quantities have been 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 is equipped with a very flexible Electron Cyclotron Resonance (ECR) system, with two independently supplied clusters each composed of 3 X2 gyrotrons, providing up to 3 MW of ECR power. This allows to generate in L-mode plasmas a Switched EC Current Drive (SECCD) [3], i.e. to drive, during a discharge, alternatively positive or negative local ECCD at constant total input EC power. The EC beams are alternatively injected at a constant frequency inside the plasma, maintaining symmetric aiming of the beams and the same power deposition profile. Due to uncertainties on the injected total input power $P_{ECH}$, 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 and thus adjust $P_{ECH}$. The basic idea of these experiments is indeed to decouple the contributions of specific heating oscillations from those of the current 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] for the electron energy diffusion coefficient $\chi_e$; c) in predictive mode again, using the model b) multiplied by $s^2$. The latter choice is motivated by the fact that in the RLW model the reduction of transport is related to an increase on the local shear, $\chi_e \propto |1/s|$, which is adequate for TCV discharges in case of negative or large positive shear. The two free parameters involved in the models have been determined to adequately reproduce the measured $T_e$ for the corresponding ECH discharges. The plasma response has thus been studied in presence of SECCD, to understand the differences in time scales and transient behaviour between the various models employed and under different experimental conditions such as modulation 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 which turned out to be associated to SECCD discharges. In the simulations presented here only a few parameters ($I_{ECCD}$, $T_e$) have been varied each time, the others ($\kappa$, $\delta$, $P_{ECH}$, $n_e$, $T_i$, $I_p$) being fixed, which is of course very 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, consistent with experiments, and is found not to be long enough for a steady-state to be reached, as the simulated parallel electric field is not relaxed yet. Simulations with much longer modulation times

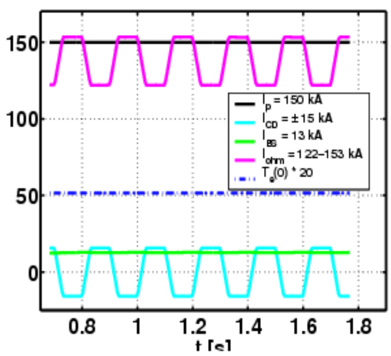


Fig. 1

have been done, identifying the steady-state modulation frequency around 3 times larger than the experimental one. During the transition from one phase to the other, $I_{ECCD}$ is imposed to vary along its extreme values in 30 ms and is held constant until the end of the phase. Fig. 2 and 3 compare the shear modulation, which reaches its maximum at the deposition location $\rho_{dep}$=0.22, for the two interpretative runs, respectively at fixed or varying $T_e(\rho)$. One observes the shear behaviour is essentially the same, with $\Delta s$=0.4 at $\rho_{dep}$. The latter case can be compared with a previous rough modelling based on electrodynamics calculations which is 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 co- to cnt-phase, while the $q$=1 surface stays constantly in the plasma core and $q(\rho_{dep})$ oscillates between respectively 1.2 and 1.4. The $j_{ECCD}$ used in the rough modelling is 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.

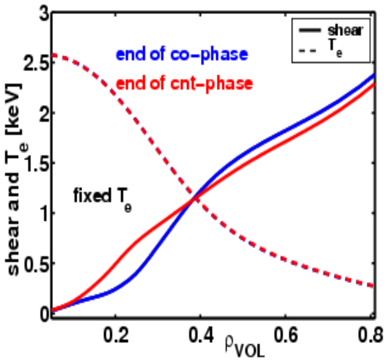


Fig. 2

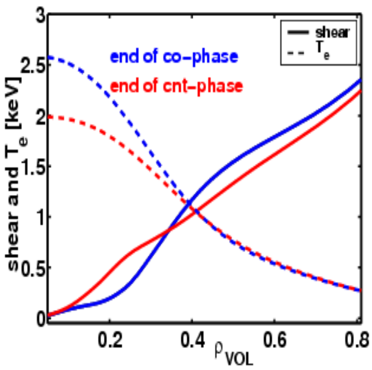


Fig. 3

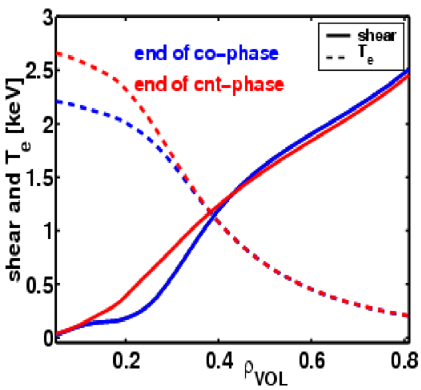


Fig. 4

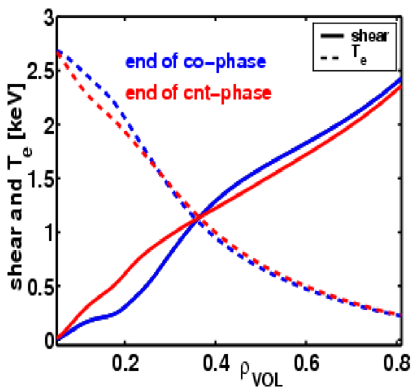


Fig. 5

Concerning the simulations involving $\chi_e$ models, the location and extent of the shear modulation is in good agreement with the interpretative results, as evident from Fig. 4 and 5, confirming the robustness of the shear modelling. For the RLW model (Fig. 4), though, the calculated $T_e$ profiles behave in quite the opposite way as the experimental data, with the higher central value corresponding to the end of the cnt-phase, where the magnetic shear is higher. This can be explained by the already mentioned dependence of the model on the inverse shear. The linear-dependent model, instead, predicts a slightly higher $T_e$ for $\rho < 0.25$.

The interpretative modelling is consistent with the fact, predicted by gyrokinetic linear simulations [2], 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 investigate transport properties at larger $s$ by shifting the SECCD deposition location more off-axis. The radial deposition of the ECH power has been varied to $\rho_{dep} = 0.5$ to study the range of shear modulation accessible at such radius. By driving an $I_{SECCD}$ with a maximum of about 10 kA, peaked at the new $\rho_{dep}$, $s$ spans from 1.4 to 1.65 and if $I_{SECCD}$ increases to 17 kA $s$ ranges 1.3-1.8.

A more recent series of SECCD discharges with double ECH power (i.e. 2+2 gyrotrons) and a 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 obviously complicates the correct interpretation of the observed electron temperature modulation. Indeed, 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 Fig. 4. It confirms experimentally that the $q$ profile is indeed modified locally, but also explains the fact that in these new discharges no significant effect on $T_e$ is observed. The identification of the toroidal and poloidal mode numbers for these modes should nevertheless allow a possible validation of the ASTRA modelling by comparison with the simulated rational $q$ surfaces, but so far they have not been used as a complementary experimental data set on the swing-ECCD studies.

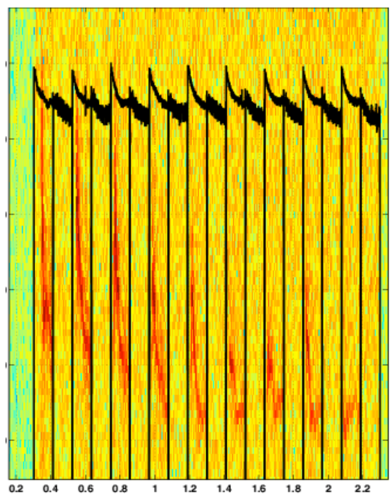


Fig. 6

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