

## Turbulence Modelling of T-10 ECRH Switch-off Experiments

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**Switch-off experiments** In the T-10 tokamak at the Russian Kurchatov Institute ( $R_0 = 1.50$  m,  $a_{\text{lim}} = 0.30$  m, circular plasma cross-section,  $I_p \approx 180$  kA,  $B_t \approx 2.35$  T), experiments with strong and very localised electron cyclotron resonance heating (ECRH) are conducted [1,2]. In a typical experiment a low density plasma (typically,  $\bar{n}_e = 1.8 \times 10^{19} \text{m}^{-3}$ ) is heated with 460 kW off-axis ECRH. When positioned such that sawteeth are just stabilised (i.e.  $q(0) \gtrsim 1$ ) it was found that switching off ECRH does *not* result in an immediate decrease of the electron temperature  $T_e$  inside the heating radius  $\rho_{\text{dep}}$  (see fig. 1). This delay can be up to 20 ms, significantly longer than the normal energy confinement time in these discharges. By contrast, outside  $\rho_{\text{dep}}$   $T_e$  decreases immediately after the heating is switched off.

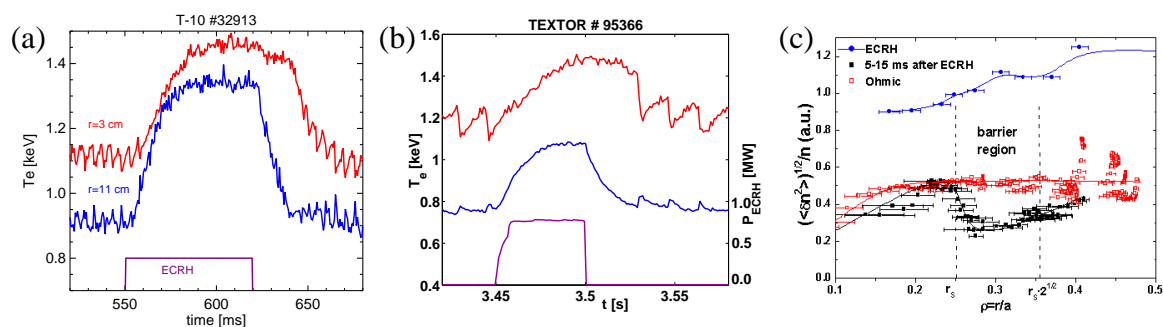


Figure 1: (a)  $T_e(t)$  measured by ECE in the T-10 tokamak. After ECRH switch-off at  $t = 620$  ms  $T_e$  outside the heating radius (blue line) starts decreasing immediately, while the decrease in central  $T_e$  (red line) is delayed by at least 20 ms. (b) Similar measurements on TEXTOR. (c) The normalised density fluctuation level measured with O-mode reflectometry in T-10. With ECRH heating the fluctuations increase over the full measured range (blue points). A few ms after switching off ECRH the fluctuations decrease around the heating radius (black points). Fluctuations in the ohmic phase are plotted for comparison (red points).

These experiments have been reproduced in the tokamak TEXTOR ( $R_0 = 1.75$  m,  $a_{\text{lim}} = 0.46$  m, circular plasma cross-section,  $I_p \sim 350$  kA,  $B_t \sim 2.35$  T), operated by the Trilateral Euregio Cluster (TEC) [2]. The TEXTOR experiments confirmed the strong dependence on ECRH power and duration; if the ECRH pulse is too long or the power is too high, the effect is smaller or not observed at all.

The delay of heat loss from the core indicates reduced heat transport due to a local suppression of the turbulence, an internal transport barrier (ITB). This is confirmed by measurements of density fluctuations with O-mode reflectometry, [3,4] which reduce to below ohmic level in the heating region right after ECRH switch-off.

A mechanism to explain the observations was put forward [1,2]. Earlier observations in T-10 have indicated the importance of low magnetic shear near low order rational  $q$ -surfaces for ITB formation [5]. In the present experiments, a low shear region near  $q = 1$  is assumed to be present in the central part of the plasma and an ITB is formed. However, the resulting

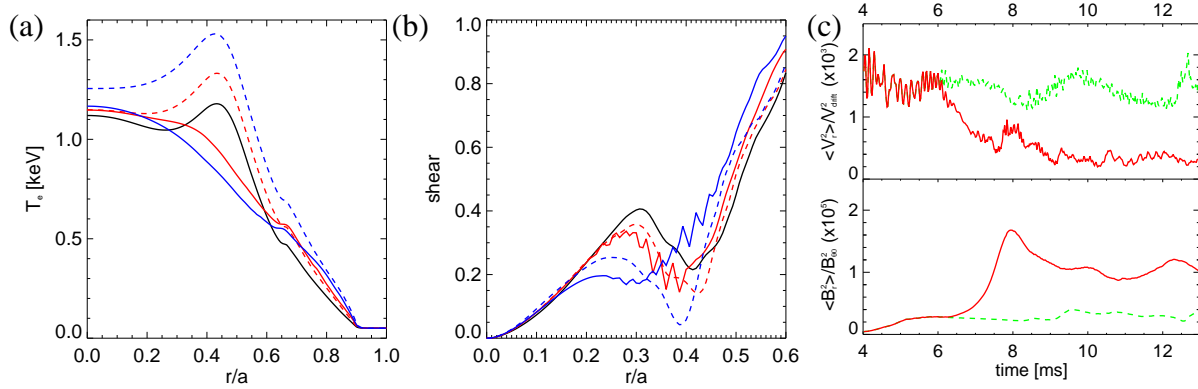


Figure 2: (a)  $T_e$ -profiles calculated by CUTIE just before switching off ECRH (black line), 2.2 ms after switch-off (red) and 6.5 ms after switch-off (blue). Dashed lines show profiles at the same times for the control run with continued ECRH. (b) Magnetic shear from the simulations. Colours and drawn/dashed lines are as in plot a. Note that not the full radius is shown. (c) Overall fluctuation levels in the simulated switch-off (red lines) and in the control run (green lines). Electrostatic fluctuations ( $\langle v_r^2 \rangle / v_{\text{drift}}^2$ , top) show a clear reduction after the switch-off (at 6.0 ms), while magnetic fluctuations ( $\langle B_r^2 \rangle / B_{00}^2$ , bottom) increase.

higher central temperature leads to more current running in this region, increasing the shear and thus limiting the strength of the barrier. Switching off the ECRH may then initiate a current redistribution which transiently lowers the shear to almost zero, enhancing the ITB.

**Numerical model** To further study the role of turbulence in these experiments and to test the proposed role of the  $q$ -profile, numerical calculations are being done with CUTIE, a global electromagnetic turbulence code [6,7]. It describes a full tokamak plasma in a periodic cylinder geometry with toroidal corrections, using a reduced two-fluid model, excluding fast magnetosonic waves. The equations used describe such physical effects as visco-resistive tearing, ballooning, drift-Alfvén and  $\eta_i$  modes. Seven 'fluctuating fields' (electric and magnetic potential, potential vorticity, electron density, toroidal fluid momentum and the temperature fluctuations of both species) with a flux surface average of zero, are Fourier transformed in poloidal and toroidal angle, and solved using a radial finite-difference scheme. Flux surface averaged profiles are solved separately but co-evolved with the 3D fluctuations, allowing strong non-linear interactions between turbulent transport and profile evolution.

The ion gyroradius is resolved in radial direction, and a spectral resolution of  $m \times n = 64 \times 32$  was chosen to avoid aliasing of the higher spectral modes. For the simulations described in this paper, CUTIE was started from initial profiles roughly corresponding to T-10 measurements just before the ECRH switch-off. This includes information on  $T_e$ ,  $n_e$  and  $Z_{\text{eff}}$  and the profile of the absorbed ECRH power (460 kW at  $r/a = 0.46$  with a width of about 3 cm). It should be stressed that very little is known about the experimental  $q$ -profile, while the proposed mechanism depends critically on details of  $q$ . As a first estimate, a simple parabolic  $q$ -profile with  $q_a = 3.9$  and  $q_0 = 1.1$  (values from the experiment) is taken as start of the calculation. The code will then develop  $q$  further, although there is no guarantee that the CUTIE-profile will resemble the experimental profile.

Due to the long run time of CUTIE even on a fast computer system, a steady state was not yet reached in the simulations, and therefore after 6 ms simulation time the ECRH power was switched off although the profiles were still evolving. A parallel run with continued ECRH was done for comparison.



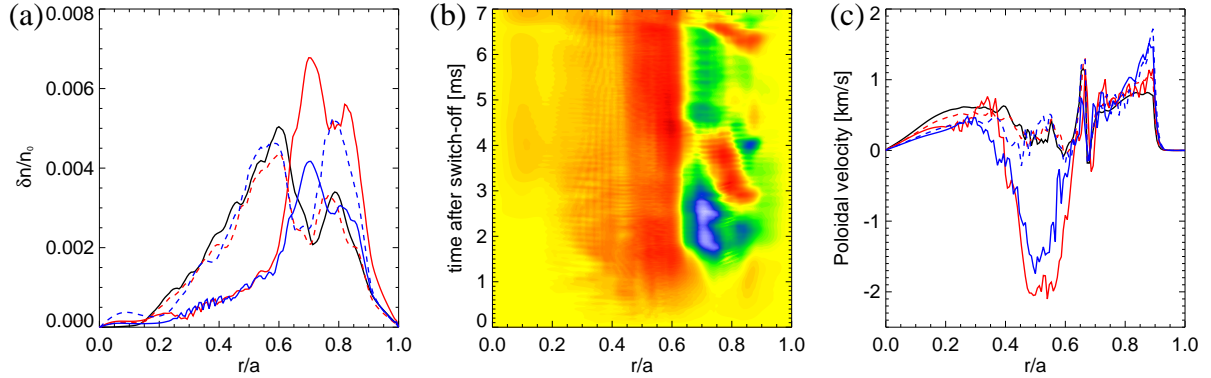


Figure 4: (a) Profiles of density fluctuations  $\delta n/n_0$ . Colours and linestyle have the same meaning as in fig. 2a,b. (b) radius vs. time plot of the difference in density fluctuations between switch-off and control run. Yellow indicates no difference, red a reduction in turbulence while green and blue indicate an increase. (c) profiles of the poloidal rotation of the plasma, again with colours and linestyles as in fig. 2a,b.

flow with a strong velocity shear. This zonal flow sets in right after ECRH switch-off and corresponds to the location of turbulence suppression in the simulation, see fig. 4c. It is absent in the control run with continued heating.

**Conclusions** Simulations of T-10 ECRH switch-off experiments with the CUTIE turbulence code have been started. Although the present runs have not yet reached steady-state, mainly due to the slow running of CUTIE, a clear reduction in turbulence, especially the density fluctuations just outside the heating region, is observed after switch-off. This reduction could be linked to the occurrence of a poloidal zonal flow with strong velocity shearing, a well known mechanism for turbulence suppression. The central electron temperature in the simulations stays constant after the switch-off. However, since  $T_e(0)$  in the control runs with continued ECRH keeps rising, the relation of this delay to the experimental observations is not yet clear. A link with the magnetic shear or  $q$ -profile can on the basis of current simulations not be made.

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