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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_{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 ρ_{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 ρ_{dep} T_e decreases immediately after the heating is switched off.

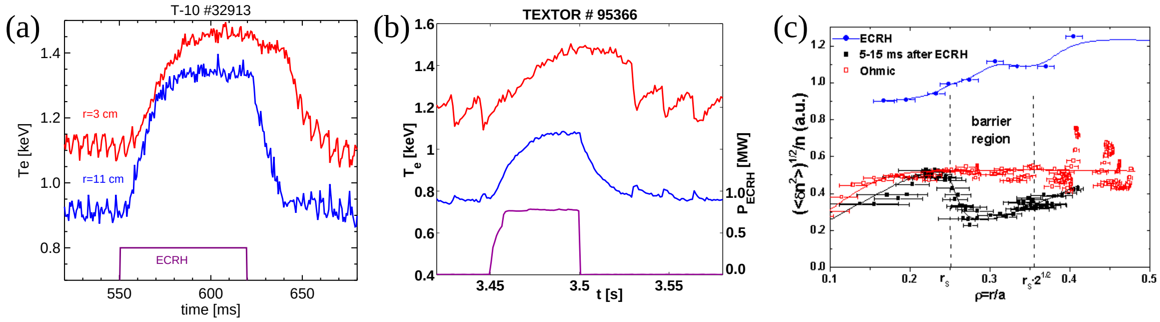

Figure 1: *(a) $T_e(t)$ measured by ECE in the T-10 tokamak. After ECRH switch-off at $t = 620$ ms T_e outside the heating radius (blue line) starts decreasing immediately, while the decrease in central T_e (red line) is delayed by at least 20 ms. (b) Similar measurements on TEXTOR. (c) The normalised 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_{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

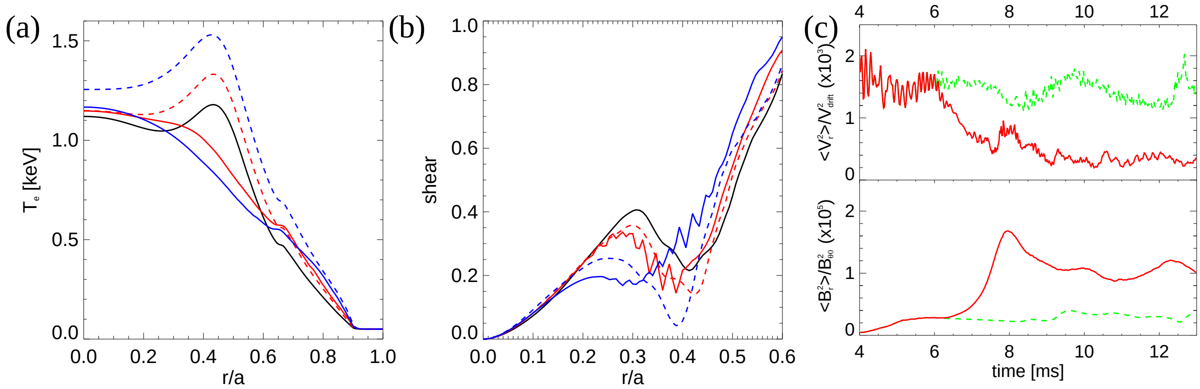

Figure 2: *(a) T_e-profiles calculated by CUTIE just before switching off ECRH (black line), 2.2 ms after switch-off (red) and 6.5 ms after switch-off (blue). Dashed lines show profiles at the same times for the control run with continued ECRH. (b) Magnetic shear from the simulations. Colours and drawn/dashed 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 ($\langle v_r^2 \rangle / v_{drift}^2$, top) show a clear reduction after the switch-off (at 6.0 ms), while magnetic fluctuations ($\langle B_r^2 \rangle / B_{\theta 0}^2$, 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 η_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 seperately but co-evolved with the 3D fluctuations, allowing strong nonlinear 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_{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.

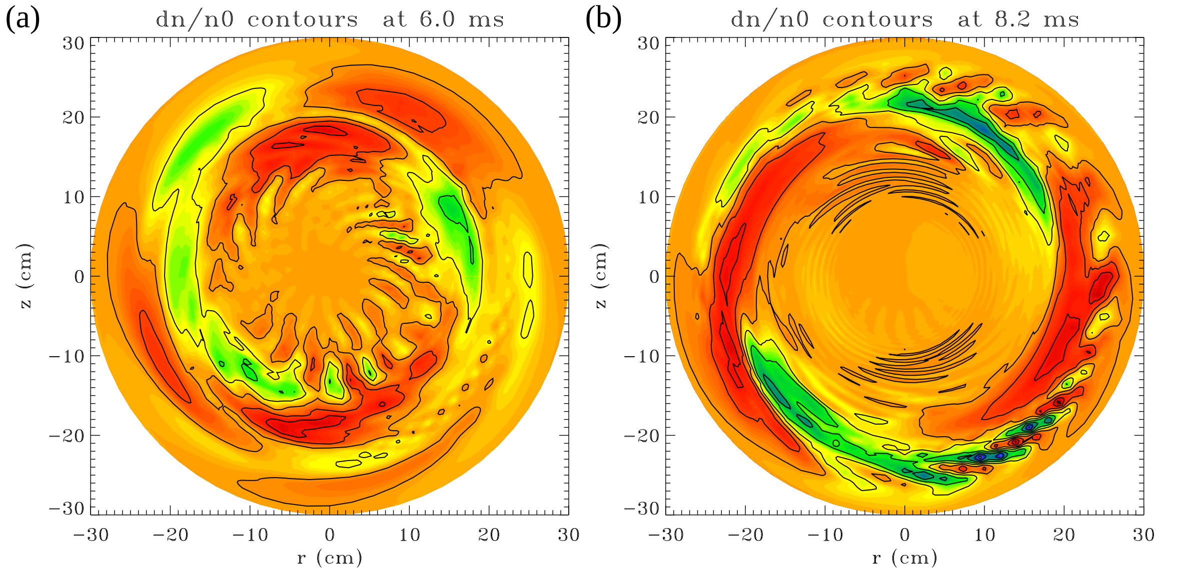

Figure 3: *Contour plots of density fluctuations, $\delta n/n_0$, in a poloidal cross-section of CUTIE simulations. The colour coding in both plots is the same, with orange representing values around zero, yellow & green positive and red negative. (a) Before switch-off. (b) 2.2 ms after switch-off.*

Results of the simulations In fig. 2, simulated profiles of T_e and the magnetic shear are shown. The simulated T_e develops an off-axis maximum at the heating location, that is not observed in the experiment. Although a fixed density source is used in the simulations, resulting in a heat sink roughly at the location of the dip in T_e, steady state calculations with a power balance code show that this can not fully account for the profile shape. Since the profiles are still evolving, the hollow T_e-profile could very well be transient. While after switch-off of the ECRH power no immediate decrease in central T_e is observed, the control run shows a pronounced *rise* in T_e. On the basis of T_e alone it is therefore difficult to claim a delayed heat loss. Also outside the heating radius T_e hardly drops, contrary to experimental observations.

The magnetic shear in the region $0.15 < r/a < 0.35$ is reduced with respect to the situation before switch-off. Also in case of continued heating the shear is higher in this region. However, continued heating causes a stronger shear reduction in the heating region than the switch-off. These results do not give any conclusive indication as to wether shear plays a role in the experiment.

A significant change in turbulence level right after the switch-off is observed, however. Fig. 2c shows that electrostatic turbulence is strongly suppressed. This is measured by $\langle v_r^2 \rangle / v_{drift}^2$, in which angled brackets denote an average over the full plasma. The magnetic turbulence as indicated by $\langle B_r^2 \rangle / B_{\theta 0}^2$ rises 2 ms after the switch-off.

In figs. 3 and 4 this is illustrated in more detail for the density fluctuations. These figures show that after the switch-off $\delta n/n_0$ is reduced in the area just outside the heating radius. Figure 3a shows two regions of strong turbulence; One around the heating radius ($r/a = 0.46$), the other further out. After switch-off (fig. 3b) density fluctuations inside the heating radius are quenched. Fluctuations outside the heating radius are pushed further out and increased. The maximum now corresponds to the $q = 2$ surface at $r/a \approx 0.67$. Figure 4a and b show that the rise in fluctuations around the $q = 2$ surface also occurs in the control run with continued ECRH, and is therefore not related to the switch-off.

A possible mechanism for the turbulence reduction is the occurence of a poloidal zonal

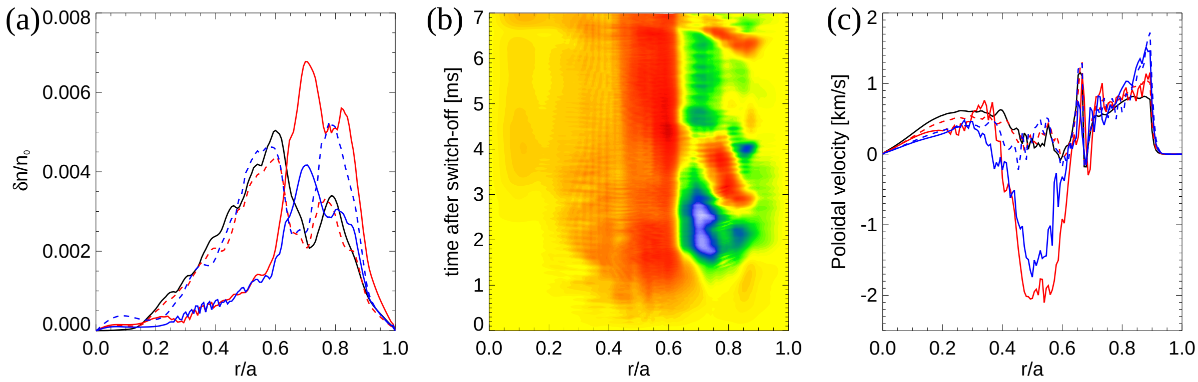

Figure 4: *(a) Profiles of density fluctuations* $\delta n/n_0$. *Colours and linestyle have the same meaning as in fig. 2a,b. (b) radius vs. time plot of the difference in density fluctuations between switch-off and control run. Yellow indicates no difference, red a reduction in turbulence while green 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 occurence 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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