2-D ECE Temperature Measurements inside Tearing Modes, Revealing the Suppression Mechanism by ECRH at TEXTOR.

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INTRODUCTION

Neoclassical tearing modes are thought to pose a limit on the reachable β (ratio of plasma pressure over magnetic pressure) in ITER, so it is important to develop techniques to control or suppress these instabilities. A set of tearing mode suppression experiments on the TEXTOR tokamak (limiter, circular plasma cross section, R_0=1.75m, a=0.47m) is described, that focuses on the suppression by heating (ECRH). The unique combination of tools on TEXTOR (the Dynamic Ergodic Divertor (DED) to make islands [1], ECRH to suppress them [2] and ECE-Imaging to diagnose them [3]) enables a detailed study of the suppression process.

The tearing mode suppression by heating is often neglected. Electron cyclotron current drive (ECCD) is thought to be a more efficient way to suppress (neoclassical) islands. The low electron temperature in TEXTOR makes the heating effect dominant for these experiments [2].

The suppression process can be split into two independent parts: the formation of a peaked temperature profile in the island and the actual suppression of the island. The heating efficiency is determined by the transport in the island. The suppression is governed by the modified Rutherford equation (the higher temperature in the island lowers the resistivity, which leads to an increased parallel current). A comparison of the observed suppression rates with theory is given.

In ITER, ECRH might be a significant effect compared to ECCD, depending on the heat transport properties inside the ITER islands. In any case, ECRH facilitates the suppression of the neoclassical tearing modes.

EXPERIMENTAL SET UP AND DATA REPRESENTATION

The DED is a perturbation field experiment consisting of 16 helical coils on the high field side of TEXTOR, generating a perturbation field with strong m/n=2/1 and 3/1 components. The 2/1 component of this field generates a large 2/1 magnetic island that is strongly locked to the perturbation field. This very predictable and controllable island is heated at the high field side by ECRH. The moveable launcher of the 140 GHz, 800 kW gyrotron is used to position the power at the resonant surface. The evolution of the island is followed in detail by the 2D ECE-Imaging diagnostic, which measures the electron temperature in an 8 by 16 array of sampling volumes in the poloidal plane with a 1 cm spatial resolution. The ECEI data, taken at the low field side, only covers a small section of the poloidal circumference of the q=2 surface. To get a comprehensive view of the (low field side) mode structure of the 2/1 island, a poloidal reconstruction is used. The time history of a full rotation period of the plasma is mapped onto a poloidal shell, as shown in figure 1. This reconstruction clearly shows the elliptically deformed plasma core and the peaked temperature profile inside the island.

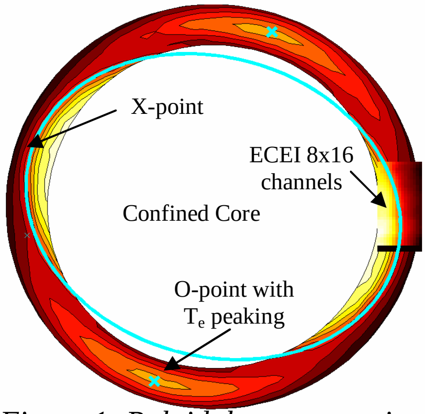

Figure 1: Poloidal reconstruction of ECRH heated island

The two main properties of the island to be determined are the island width *w* and the temperature profile inside the island. To determine the island width *w*, an ellipse is fitted to a temperature contour of the (deformed) central plasma. The difference between the major radius *a* and minor radius *b* of this ellipse gives the displacement of that contour, which is a measure for the full island width $w \approx 1.5(a-b)$ [4]. The maximum temperature in the island occurs at the O-point. The temperature profile inside the island is evaluated on a circle through the O-point, to avoid possible (relative) calibration errors. From this T_e profile the temperature difference ΔT_e between O-point and separatrix is determined.

Figure 2 shows typical time traces of the relative temperature peaking $\Delta T_e/T_e$ and island width *w*. Directly after switch on of ECRH, the temperature inside the island rises to typically 25% above the separatrix temperature. Then, on a slower time scale, the island starts to shrink to typically half the initial width (which also lowers the temperature peaking again). After switch off of ECRH the peaking disappears almost instantaneously (within an energy confinement time of the island, about 1 ms) and the island width slowly relaxes back to the initial width of about 12 cm.

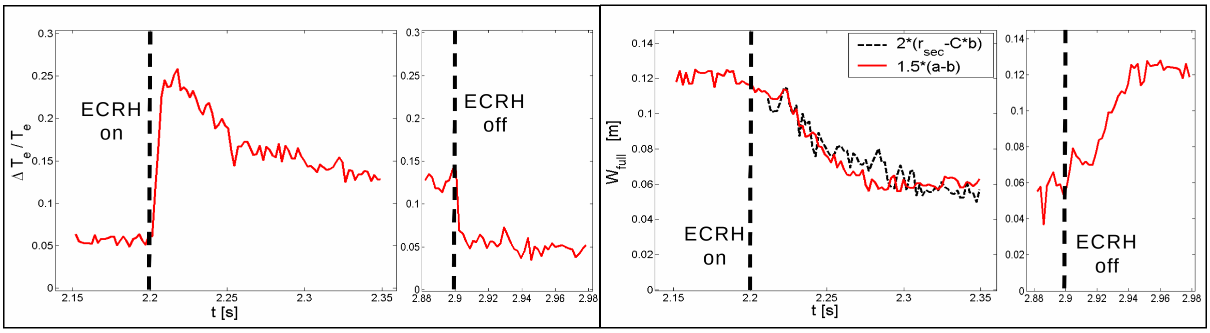

Figure 2: Typical time evolution of relative T_e peaking and island width.

The suppression process can be split into two independent parts: the heating and the actual suppression, treated separately in the following chapters.

HEATING: POWER BALANCE INSIDE ISLAND

The effectiveness in which a temperature peaking forms inside an island depends on the electron heat transport inside the island. The detailed knowledge of the temperature profile and the ECRH power input in the island enables a power balance analysis. Inside the island, ECRH is the only significant heating source. Numerical evaluation of the power balance equation ($q_e = -n_e \chi_e \nabla T_e$) applied on the island geometry reveals that over the largest part of the island the electron thermal diffusivity χ_e is about 1 to 1.5 m^2/s. A power balance analysis of the entire plasma reveals that the transport in the ambient plasma is comparable to the transport inside the island. For the ambient plasma χ_e is typically 1 m^2/s inside the deposition radius of ECRH and a few times higher outside the deposition radius.

SUPPRESSION: THE MODIFIED RUTHERFORD EQUATION

The time evolution of the island width is governed by equation 1, relating the stability parameter Δ’ to the total helical current inside the island region [5]. The parameter Δ’ is the step in the poloidal flux function over the island region, and is a measure for the ‘willingness’ of the plasma to create an island. Various contributions to the parallel current are possible. If only the inductive current due to the growth of the island is taken into account, equation 1 results in the classical Rutherford equation [6]. The inclusion of other contributions to the parallel current results in modifications of the classical Rutherford equation. Equation 2 and 3 give the modified Rutherford equation with the two modifications important for these experiments [7-11].

$$\Delta'\tilde{\psi} = 2\mu_0 R \int_{r_s-w/2}^{r_s+w/2} dy \oint j_{//}\cos(m\xi)\,d\xi \qquad \Delta' = \frac{1}{\psi}\left[\frac{d\psi}{dr}\right]_{r_s-w/2}^{r_s+w/2} \tag{1}$$

$$\boxed{0.82\cdot\tau_r \frac{dw}{dt} = r_s^2\Delta' + M_{ext} - M_{heating}} \tag{2}$$

$$M_{ext} = 2mr_s\left(\frac{w_{vac}}{w}\right)^2 \qquad M_{heating} = \frac{32\mu_0 R r_s^2 q}{B_\theta\left|\frac{dq}{dr}\right| R w^2}\cdot\frac{j_{sep}}{T_{e,sep}^{3/2}}\int_{r_s-w/2}^{r_s+w/2} dy\oint T_e^{3/2}\cos(m\xi)\,d\xi \tag{3}$$

The M_{ext} term describes the (generally destabilizing) effect of the shielding currents in the island region due to the external DED currents. The DED sets up a perturbed magnetic field resonant with the island. This will cause currents to flow inside the island region that try to compensate this external field. The $M_{heating}$ term describes the (generally stabilizing) effect of the modulated Ohmic current due to temperature perturbations inside the island (so ECRH).

The DED term M_{ext} is fully known. The vacuum island width w_{vac} = 4 cm. The ECRH term $M_{heating}$ can be evaluated numerically. The q profile and current density j_{sep} on the separatrix are estimated from the temperature profile. The left graph of figure 3 gives $M_{heating}$ as a function of time, showing it is approximately constant at 1.2 m. The Δ’ term is in principle unknown. Before the DED is switched on, there is no 2/1 island present, but after switch off of the DED the island remains, so in the DED phase Δ’ is probably close to zero.

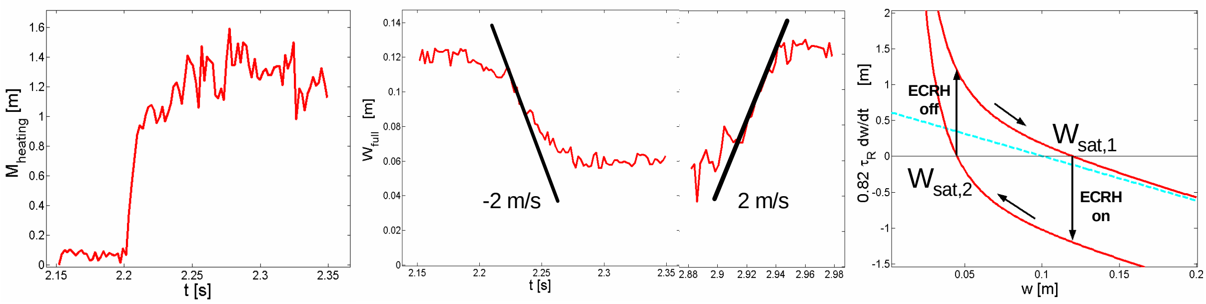

Figure 3: The suppression process: a) The heating term b) The experimentally observed growth/suppression rates c) Overview of the various terms in the modified Rutherford equation.

Directly after switch on (or off) of ECRH, coming from a steady state situation (so all other terms cancel out), the heating term $M_{heating}$ is the only one contributing to *dw/dt*. Equation 2 then predicts a suppression (or growth) rate of about 2 m/s. The middle graph of figure 3 shows the agreement of the experiment with the theoretically expected suppression and growth rates.

The relaxation to the new saturated island width (about 6 cm) is determined by the balance of $M_{heating}$ with all other terms. The right graph of figure 3 gives an overview of the suppression process. Plotted is the right hand side of the modified Rutherford equation (equals 0.82 $\tau_R\, dw/dt$) against the island width. The upper curve is composed of the Δ' and DED terms. The lower curve includes the heating term. To reproduce the observed saturated island widths, a Δ' term of the form of the dashed line had to be introduced.

EXTRAPOLATION TO ITER

In ITER a bootstrap current fraction of typically 30% is expected. To replace the lost bootstrap current inside an NTM by heating, a temperature peaking of about 20% is needed, comparable to the peaking observed at TEXTOR. Equation 4 gives the scaling for the temperature peaking, assuming narrow islands and a power deposition width smaller than the island width (the numerical factors A_1 and A_2 are assumed machine independent).

$$q_e = -n\chi_e \nabla T_e = \frac{P_{ECRH}}{r_s R} A_1 \qquad \frac{\Delta T_e}{T_e} = \frac{w\nabla T_e}{T_e} A_2 = \frac{w P_{ECRH} A_1 A_2}{r_s R n \chi_e T_e} \qquad (4)$$

To get the same temperature peaking in ITER as in TEXTOR, equation 4 requires a lower χ_e inside the ITER islands (about a factor of 6) than the χ_e~1.5 m^2/s observed in TEXTOR. So for χ_e~0.2 m^2/s in the ITER NTMs the heating effect is strong enough to compensate the lost bootstrap current, and is competitive with the expected ECCD effect. Even if inside the ITER islands χ_e~0.5 m^2/s, which is equal to the expected equilibrium χ_e at the q=3/2 surface in ITER, the heating effect is still significant.

CONCLUSIONS

The combination of ECEI, ECRH and DED enabled a detailed study of the suppression process of Tearing Modes by ECRH at TEXTOR. Large Temperature peakings of typically 25% have been observed, leading to a suppression of the DED induced islands to about half the initial width. A power balance analysis inside the island revealed a typical χ_e of 1.5 m^2/s, comparable to the ambient plasma. The measured suppression rates are consistent with theory (modified Rutherford equation).

In ITER, ECRH is likely to be able to compensate a significant fraction of the lost bootstrap current in the NTM. ECRH is competitive with ECCD if $\chi_{e,island}$<= 0.2 m^2/s. In any case, the heating effect is a significant, free side effect of ECCD experiments which always work in favor.

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