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On the Merits of Heating and Current Drive for Tearing Modes Stabilization

D. De Lazzari[1], E. Westerhof[1], B. Ayten[3] and the TEXTOR team[2]

[1] *FOM-Institute for Plasma Physics Rijnhuizen, Association EURATOM-FOM, Trilateral Euregio Cluster, Nieuwegein, The Netherlands, www.rijnhuizen.nl*

[2] *Institut für Energieforschung - Plasmaphysik, Forschungszentrum Jülich GmbH, Association EURATOM-FZJ, Trilateral Euregio Cluster, D-52425 Jülich, Germany*

[3] *Eindhoven University of Technology, Dept. of Mechanical Engineering, Control Systems Technology Group, PO Box 513, NL-5600 MB Eindhoven, The Netherlands*

Introduction

Control and suppression of neoclassical tearing modes (NTMs) can be achieved with highly localized deposition of electron cyclotron waves (ECW) at the mode location. The EC-Waves help re-establishing the missing bootstrap current, responsible for the growth of a magnetic island, via two effects, electron cyclotron heating (ECRH) and current drive (ECCD). Although both effects have been applied successfully to experiments, showing a predominance of ECRH for medium size limiter tokamaks (TEXTOR, T-10) and of ECCD for mid-to-large size divertor tokamaks (AUG, DIII-D, JT-60), the conditions determining their relative importance are still unclear. We address to this problem with a numerical study [1] focused on the relative merits of heating and current drive to the temporal evolution of NTMs as described by the modified Rutherford equation. The model has furthermore been benchmarked with experiments on tearing mode control by ECRH and ECCD, performed in TEXTOR [2]. The modeling confirms the experimental observation, that in TEXTOR heating inside the magnetic islands is the dominant effect responsible for the stabilization.

Theoretical background

The ECW deposition inside the island can lead to the stabilization of the mode either directly through a noninductive current j_{CD}, or indirectly, by a perturbation of the temperature profile resulting in a perturbation of the inductive current j_H. These effects can be described in the frame of the modified Rutherford equation MRE,

$$0.82\frac{\tau_r}{r_s}\frac{\mathrm{d}w}{\mathrm{d}t} = r_s\Delta_0'(w) + r_s\Delta_{DED}' - r_s\Delta_{CD}' - r_s\Delta_H' \,, \tag{1}$$

where τ_r is the resistive time scale at the resonant radius r_s of the mode and Δ_0' is defined as the logarithmic discontinuity in the radial derivative of the perturbed magnetic flux function ψ across the island. The second term in the rhs of equation (1) represents the drive by the external perturbation fields. In the case of TEXTOR this refers to the dynamic ergodic divertor (DED) perturbation,

$$r_s\Delta_{DED}' = 2m\frac{w_{vac}^2}{w^2}\cos(\Delta\phi) \,, \tag{2}$$

where m is the poloidal number, w_{vac} is the is the size of the magnetic island calculated from the resonant magnetic perturbation in vacuum, and $\Delta\phi$ is the phase difference between the tearing mode and the external perturbation field. In the case of NTM, additional terms appear in the MRE which describe, amongst others, the effects of a finite bootstrap current. For the low β applying to the TEXTOR experiments these terms can be neglected. The terms in the (MRE) describing the stabilizing contribution of ECRH and ECCD, $r_s\Delta'_{CD,H}$, can be written as product of an effectivity $\eta_{CD,H}$ times a dimensionless term $F_{CD,H}$ with a common fore-factor,

$$r_s\Delta'_{CD,H} = \frac{16\mu_0 L_q}{B_p\pi}\frac{P_{tot}}{w_{dep}^2}\eta_{CD,H}F_{CD,H}(w^*, x_{dep}, \mathscr{D}) \ . \tag{3}$$

Here μ_0 denotes the permeability of the free space, L_q the shear length and B_p the poloidal field at the mode resonant radius. A normalized Gaussian distribution has been assumed for the power deposition profile, as well as for the current profile, with P_{tot} the total injected power and w_{dep}, the full e^{-1} power (current) density width. $F_{CD,H}(w^*, x_{dep}, \mathscr{D})$ depends only on geometrical parameters like the normalized island width $w^* = w/w_{dep}$, the displacement of the power deposition from the resonant surface $x_{dep} = r_{dep} - r_s$ and $\mathscr{D}$ indicates the dependence on a possible power modulation. The efficiency with which the power generates a current perturbation either by direct drive or through the generation of a temperature perturbation is indicated by η_{CD} and η_H, as

$$\eta_{CD} = \frac{I_{CD}}{P_{tot}} \qquad \eta_H = \frac{3w_{dep}^2}{8\pi R n_e \chi_\perp k_B}\frac{j_{sep}}{T_{sep}} \ , \tag{4}$$

where the perpendicular heat conductivity $\chi_\perp$ is assumed to be a constant; furthermore we denote with R the major radius, n_e the electron density, k_B the Boltzmann constant, j_{sep} and T_{sep} the inductive part of the current density and the temperature at separatrix, respectively. The η_H depends on the perpendicular heat conductivity which is, in fact, poorly known. Experimental results [3, 4], indicate that, in the presence of ECRH, $\chi_\perp$ is comparable to the heat conductivity in the background plasma.

Numerical results

Observing the current drive and the heating effectivity for different tokamaks, as shown in table 1, these are found to be approximately identical for TEXTOR and of the same order of magnitude for AUG. This suggests a direct comparison for the case of continuous power

	η_{CD}	η_H
TEXTOR	2.5	2.8
AUG	$4-6$	$5-9$
ITER	5.7	0.4

Table 1: *Typical values of $\eta_{CD,H}$ in units of $[kA]/[MW]$. Parameters used to determine $\eta_{CD,H}$ refer to datasets reported in [2] for TEXTOR and in [5, 6] for AUG. In the case of ITER, our calculations refer to the so called "scenario 2" [7].*

deposition at the r_s (i.e. $x_{dep} = 0$ and $\mathscr{D} = 1$), shown in figure 1. The plot shows the trend of $N_{CD,H} = F_{CD,H}(w^*, x_{dep} = 0, \mathscr{D} = CW)$, which are found to take the same value at $w^* = 1$. In the region $w^* \ll 1$ current drive appears more than one order of magnitude more effective than the heating. The efficiency of the former scales as a constant, while for the latter, it grows linearly. In the region where $w^* \gg 1$ this trend is opposite: N_H approaches a constant and N_{CD} is decreasing quadratically as $1/w^{*2}$. Observing the typical range of the island width, during its evolution, in a particular tokamak, it is possible to determine whether the mode will be affected by either ECCD or ECRH. The extrapolation to ITER parameters, in contrast, shows η_{CD} being one order of magnitude larger than η_H.

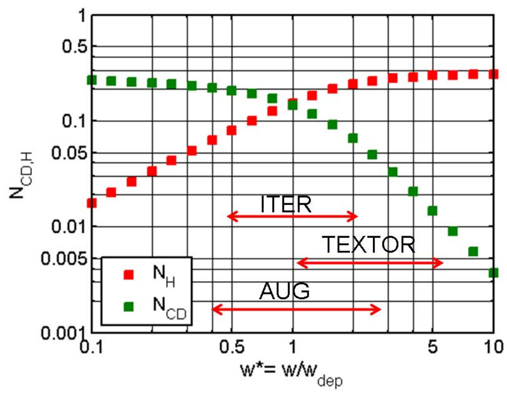

Figure 1: *Geometrical efficiency for ECCD and ECRH (green and red squares, respectively), calculated at $x_{dep} = 0$ with continuous power deposition. Red arrows refer to the typical range of a $3/2$ island in AUG and ITER, and of a $2/1$ island in TEXTOR.*

Application to TEXTOR experiments

For a medium-size tokamak like TEXTOR, experiments [2, 3] on the suppression of resonant magnetic perturbations (RMP) induced tearing modes confirmed the island suppression is almost independent on the current drive. These measurements are compatible with the theoretical predictions (see red arrows in figure 1), since the typical 2/1 island detected is larger than the deposition width. A benchmark of the MRE is performed by comparing the simulated reduction in saturated island width, according to equation (3), for ECRH and ECCD with the experimental data presented in [2]. In order to calculate the effectivity of the heating η_H, the heat conductivity and the plasma parameters as obtained in [2] are used, while the current drive efficiency η_{CD} is obtained from beam tracing calculations. In particular, two radial deposition scans with and without significant ECCD further confirm the dominance of ECRH over ECCD, (see figure 2). The latter does not appear to influence the value of the saturated island width (parameters are reported in the caption of the figure). Different symbols refer to data taken on different days which may imply slight variations in the position of the $q = 2$ surface. The model, although qualitatively compatible with experimental data, results in a symmetric suppression around the resonant radius $r_s \approx 28$cm which does not match the antisymmetric trend of the data (see black solid lines). This could be due to a modification in the magnetic equilibrium in response to the heating well outside the island resulting in a further destabilization for $r_{dep} < r_s$ and a further stabilization for $r_{dep} > r_s$. The data from [2] have also been used to benchmark the dependence on the modulation (see equation (3)) as shown in figure 3.

Conclusion

The paper has shown the possibility to compare the effect of ECCD and ECRH on tearing mode stability by describing their contribution to the Rutherford equation with a parallel structure. This formulation allows one to separate the machine-related parameters from the geometrical properties of the deposition, namely deposition width, location and modulation. A first

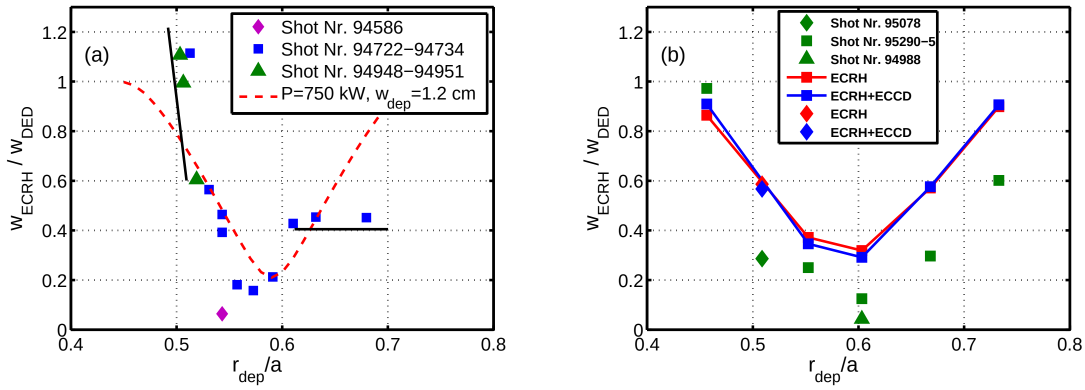

Figure 2: *Suppression of the 2/1 magnetic island as a function of the radial deposition displacement (normalized to the minor radius, $a = 47$cm) for different toroidal injection angles ϕ and deposition width at full power $P = 750$kW: (a) $\phi = +0.5^\circ$ and $w_{dep} = 1.2$ cm; (b) $\phi = -16^\circ$ and $w_{dep} = 4.6$ cm. The dashed curve in (a) represents the numerical calculation for the ECRH effect. In (b) green markers refer to experimental points, while the red markers refer to the effect of pure ECRH. Note that the contribution of ECCD (blue markers) is clearly negligible.*

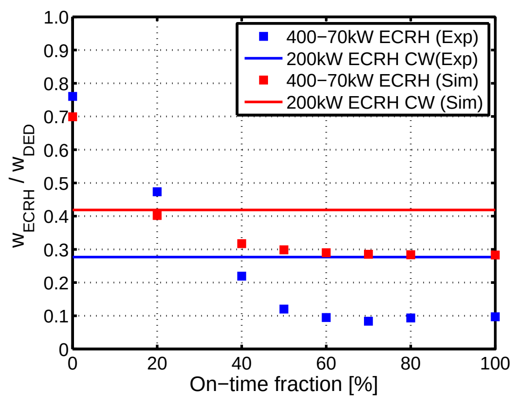

Figure 3: *Suppression of a 2/1 mode by modulated ECRH centered around the O-point as a function of the duty cycle of the ECRH high-power phase. Red markers refer to the numerical calculation while blue markers to experimental data. Solid lines refer to the continuous power deposition case. When the on-time fraction exceeds* 60%*, no further improvement on the stabilization is observed.*

benchmark of the model with experimental data shows a good agreement although there is a large uncertainty in the measurements. It is shown furthermore that for medium sized tokamaks such as TEXTOR and AUG the heating and current drive efficiencies are of the same order of magnitude, whereas in a future, large reactor like ITER, the current drive efficiency is expected to be significantly larger.

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