Analysis of NTM (de)stabilization by ECH in ASDEX Upgrade

S. Nowak[1], E. Lazzaro[1], D. Brunetti[2], B. Esposito[3], G. Granucci[1], M. Maraschek[4], H. Zohm[4]

[1]*Associazione Euratom-CNR sulla Fusione, IFP-CNR, Via R. Cozzi 53, 20125 Milano, Italy*

[2]*CRPP, Associartion Euratom-Confederation Suisse, EPFL, 1015 Lausanne, Switzerland*

[3]*Associazione Euratom-ENEA sulla Fusione, CR Frascati, C.P. 65, 00044 Frascati, Italy*

[4]*Max-Planck-Institut für Plasmaphysik, EURATOM Association, Boltzmannstr.2, 85748, Garching bei München, Germany*

Introduction

Stabilization/destabilization of the major resistive magnetohydrodynamic instabilities such as the Neoclassical Tearing Modes (NTMs) is a crucial issue for plasma confinement. The uncontrolled growth of such rotating helical modes can lead to loss of plasma energy and to disruptions. This is commonly observed for the m/n=2/1 mode on ASDEX Upgrade tokamak [1]. The aim of this work is to investigate how the NTMs can be controlled by the Electron Cyclotron Heating (ECH) and current drive (ECCD), which are powerful tools for this purpose. The local change of resistivity due to ECH affects the plasma equilibrium current density and, consequently, the safety factor q and also the helical current perturbation parallel to the magnetic field within the magnetic island. The usual tearing stability parameter Δ'_0 can be modified by moving the EC power deposition inside/outside the r_s position of the rational q=m/n surface of the mode. This crucial parameter can be calculated starting from the modification of the electron temperature T_e by ECH evaluating the favourable or unfavourable changes of plasma current density gradient $J'=J_0[(T_e/T_{e0})^{3/2}]'$. The Δ'_0 calculation is obtained by using the following analytic expression [2] which embodies toroidal and shaping effects like the Shafranov's shift and elongation of magnetic surfaces:

$$\Delta_0' = -2\sqrt{\beta^2/4\alpha^2 + \gamma/\alpha}\,(\pi\lambda)\cot(\pi\lambda)$$

where β and γ are expressed in terms of curvilinear coordinates and λ is a function proportional to $J_0\,[(T_e/T_{e0})^{3/2}]'\,q^2/q'$. The $T_e(r)$ profile refers to the profile across the island X-point. The effect of the heating on the unperturbed temperature ($T_{e,u}$) can be parameterized through a local perturbation of the temperature ($T_{e,p}$) in terms of injected power ($\div\varepsilon$) and width (w) of the power density deposition profile at a given poloidal location ρ_{dep} :

$$T_{e,p} = T_{e,u} + T_{e,u}\,\varepsilon\exp(-(\rho-\rho_{dep})/w)^2$$

In Figs.1-2 the dimensionless parameter $r_s\Delta'_0$ is plotted against $(\rho-\rho_{dep})$ for a set of ε values from 0.1 to 0.4, corresponding to a temperature increasing of ~ 100, 200, 300, 400 eV and for w=0.055 (~ 2.5 cm) and w=0.11 (~ 5 cm). The EC absorption location for a discharge discussed later is indicated on both plots. For EC power deposition outside the resonant q surface the stability parameter is stabilizing (<0) for the NTM control, while inside Δ'_0 is generally destabilizing (>0), except at some position for narrow w=0.055, depending on the local q gradient (Fig. 3), or for large w and low power, as w=0.11 and ε=0.1, where Δ'_0 becomes less stabilizing.

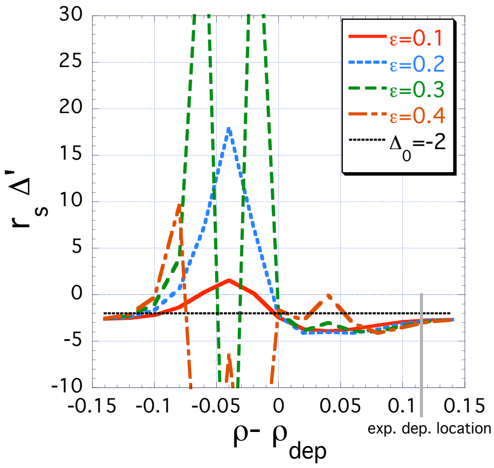

Fig.1: $r_s\ \Delta'_0$ for ε=0.1, 0.2, 0.3, 0.4 with w=0.055.

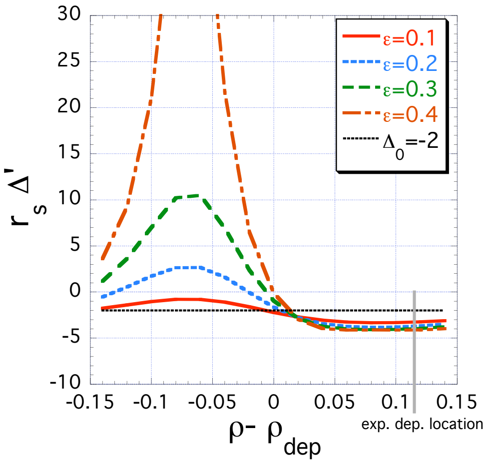

Fig.2: $r_s\ \Delta'_0$ for ε=0.1, 0.2, 0.3, 0.4 with w=0.11.

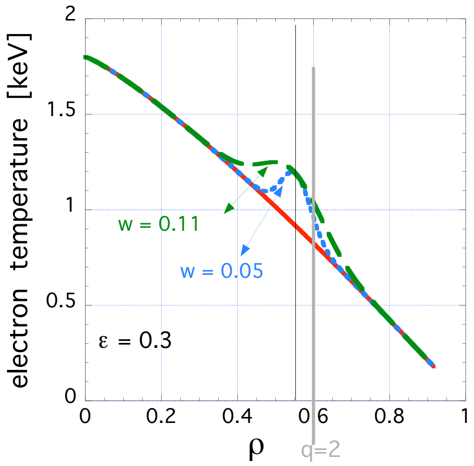

Fig.3: perturbation of Te for ε=0.3 and w=0.055-0.11 with EC deposition inside the resonant q=2.

The electron temperature in Fig.3 is close to a typical experimental profile as provided by the Electron Cyclotron Emission (ECE) diagnostic during the ECH in disruptions discharges.

This analysis has been applied to such AUG discharges with full e^{-1} power density profile dimensionless width w~0.055.

The experimental deposition was around $\rho-\rho_{dep} = 0.115$.

Stability analysis on ASDEX Upgrade data

The NTMs stability analysis has been performed in experiments on disruption avoidance in high β_N scenarios where the mode control was performed by using localized injection of EC power. The time evolution of these modes at the rational surface r_s is modelled by a Generalized Rutherford Equation (GRE) [3] including stabilizing and destabilizing terms as Δ'_0 by the equilibrium current gradient, Δ'_{bs} from the perturbed bootstrap current, Δ'_{GGJ} due to the curvature effects, Δ'_{pol} due to the ion polarization current, Δ'_w due to eddy currents in the resistive wall and two more additional stabilising terms describing the heating, Δ'_H, and current drive Δ'_{CD}, effects of the EC power injected to replace the bootstrap current. Since the combination of $\Delta'_{GGJ} + \Delta'_{pol} + \Delta'_w$ is not sufficient to balance the major destabilizing term Δ'_{bs} in this experiments, the competition is between this term and $\Delta'_0 + \Delta'_H + \Delta'_{CD}$. We compare Δ'_0 (usually = $-m/r_s$ for m=2), calculated by using the analytic model previously introduced, and the terms $\Delta'_H + \Delta'_{CD}$ given by:

$$\Delta'_H = \frac{r_s\, L_q\, J_{//,r_s}\, \hat{P}_{ECRH}}{I_{p,r_s}\, \chi_\perp n_e\, T_e} \eta_h(w/\delta_h) \begin{cases} w & \text{for } \delta_h > w \\ \delta_h & \text{for } \delta_h \le w \end{cases} ; \qquad \Delta'_{cd} = \frac{L_q\, I_{cd}}{I_{p,r_s}\, \delta_{cd}^2} \eta_{cd}(w/\delta_h) \frac{\delta_{cd}^2}{w^2}$$

where $J_{//,rs}$, $I_{p,rs}$ are plasma current density and current at the resonant position r_s, I_{cd} is the driven current, $\delta_{h,cd}$, the full e^{-1} EC power and current density widths, $\eta_{h,cd}(W/\delta_{h,cd})$ the functions related to how much the EC heating and current drive are efficient inside the mode, $\chi_\perp$ is the perpendicular heat conductivity. In Fig. 4 the time evolution of the (2,1) mode is shown for a high β_N discharge (#26817). At t=1.34 s a disruption occurred and this was 100 ms after the switching on of the EC power. The EC deposition is about 5 cm outside the mode location. The mode is nearly locked and the island width is deduced from the contour plots of the Electron Cyclotron Emission (ECE) radiometer (blue circles). The Δ' terms in GRE are plotted in Fig.5. The dashed line represents Δ'_0=-2, while the value calculated by the analytic expression is ~ -2.1, confirming that outside the resonant q the ECH is still efficient.

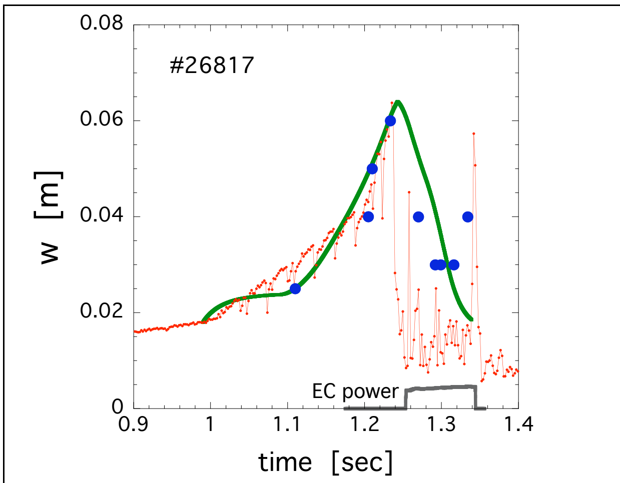

Fig.4: (2,1) mode evolution for 20% EC power: magnetic data (red line), experimental (blue circles) and simulated mode width (green).

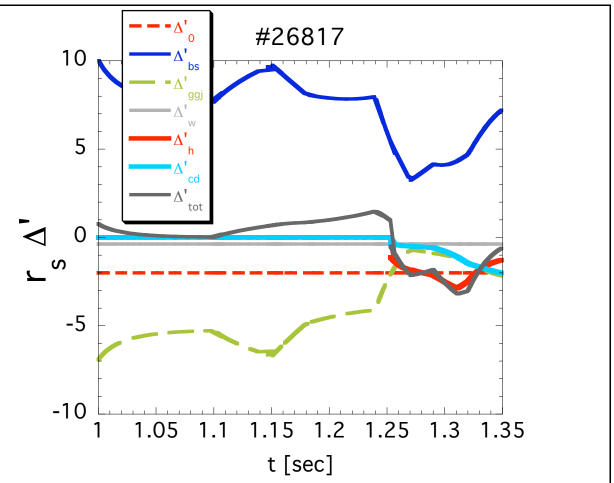

Fig.5: $r_s\Delta'$ for the simulation of Fig.4. The Δ'_{cd} contributes only for small island width where it becomes larger than Δ'_h.

The simulation requires only 20% of the 1.5 MW of EC injected power using η_h and η_{cd} efficiency values calculated for symmetric island and EC deposition exactly in its centre (O-point). A reduced helical efficiency for a typical asymmetric island has been also considered in the simulation. In Fig.6 the asymmetric island contour, superimposed on the experimental shape, is modelled using the expression for helical flux Ω deformed in amplitude [3]:

$$\Omega(x,\xi) = x^2\, 8 / w^2 - (1+\varepsilon_p x)\cos(\xi)$$

where x is the radial coordinate of the flux surface, ξ is the instantaneous phase of the rotating island and w the island width. The $\varepsilon_p<1$ (=.95) parameter is related to amplitude deformation.

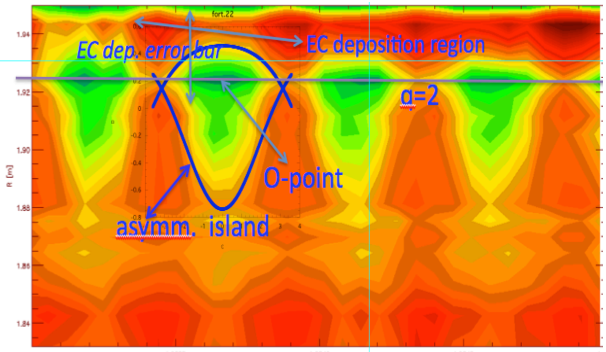

Fig.6: 2/1 mode time evolution chain with superimposed asymmetric modelled island. The error bar of the EC deposition due to uncertainties in the equilibrium reconstruction is shown.

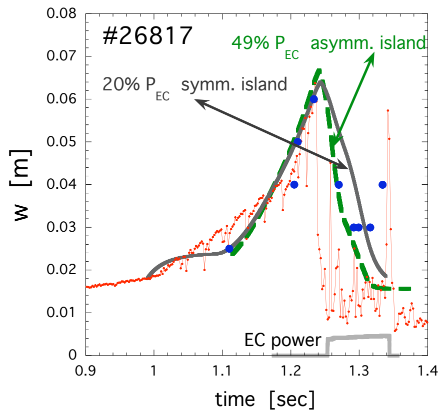

Fig.7: (2,1) evolution of the asymmetric shape as plotted in Fig.6.

In Fig. 7 the (2,1) evolution is plotted using efficiencies reduced by considering an asymmetric island, which requires a larger amount of EC power (49%) with respect to the previous 20% needed for recovering the experimental evolution [4].

Conclusions

The analysis of NTMs (de)stabilization by ECH/ECDD in ASDEX-Upgrade has been carried out for discharges in experiments on disruption avoidance. The loss of mode stabilization, even for EC deposition outside the resonant q=2 surface with a Δ'_0 still stabilizing and near to the -2 constant value, can be partially associated to geometrical effects of island deformation: different helical efficiencies calculated for symmetric/asymmetric islands lead to different stabilizing P_{EC} values.

References

[1] Esposito B et al. 2009 *Nucl. Fus.* **49** 065014
[2] Lazzaro E and Nowak S 2009 *Plasma Phys. Control. Fusion* **51** 035005.
[3] Brunetti D, Lazzaro E, De Luca F, Nowak S and Gervasini G, submitted to EPJ
[4] Urso L, Zohm H, Isayama A, Maraschek M, Poli E, ASDEX Upgrade Team and JT-60 Team 2010 *Nucl. Fus.* **50** 025010