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Tearing modes and electron temperature/pressure profile during strong electron heating with ECRH on FTU tokamak

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Introduction

On the FTU tokamak high power Electron Cyclotron Heating (ECRH) experiments have been performed with the objective of controlling MHD activity by adjusting the position of the absorbing layer $r=r_{abs}$ along the minor radius [1]. The injection from the low field side of EC waves in the O-mode polarization at f=140 Ghz corresponding to the fundamental rersonance, with a power $P^{EC} \approx$ 800 kW, has allowed the suppression of the m=1 sawtooth reconnections in a plasma with low current ($I_p \approx$350 kA) and high q_a values (≈6). As a consequence of a moderate re-shaping of the current density profile induced by the off-axis ECRH and of an increase of the local and average β_p the stability of MHD resistive modes with m=2 is altered and temperature oscillations due to rotating islands are observed to grow. The nature and dynamics of the rotating MHD modes associated with the ECRH can be understood in terms of a suitable nonlinear model. Two cases are here discussed: in the first an isolated m=2, n =1 mode is triggered by the combined effect of profile reshaping and bootstrap current contribution and the other one is characterized by toroidal coupling and uncoupling events associated with wall braking.

Experimental observations and interpretation model

In the discharges considered in this section, a small m=2 mode coexists with sawteeth during the ohmic phase. Upon ECRH injection sawtooth is stabilised whereas the m=2 mode is amplified (Fig.1). The amplitude $\tilde{T}_{e,m}$ of temperature oscillations is enhanced by the larger heat flux and by the m=2 island growth. The island width is estimated as $w \approx \tilde{T}_{e,m} / |\nabla T_e|$

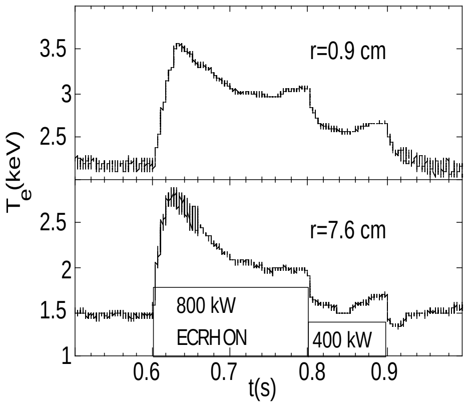

Fig.1-$T_e(t)$ on axis and at q=2surface

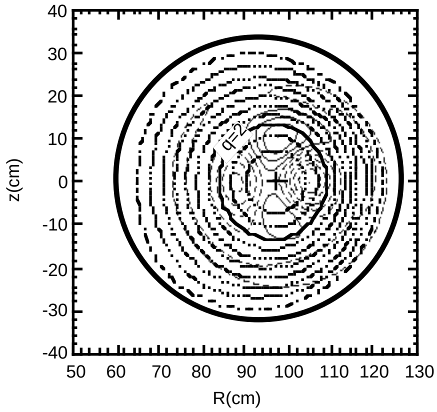

Fig.2 - Soft X- ray tomographic identification of m=2 island

As shown in Fig.2, the poloidal variation from soft X-ray tomography has a clear m=2 periodicity. The phasing between the oscillations in ECE and soft-X diagnostics, placed at different toroidal angles, is consistent with a toroidal order n=1. Although the oscillations disappear when ECRH is still on , of the electron temperature profile show (Fig.3) that the local loss of thermal insulation persist during the whole heating pulse.

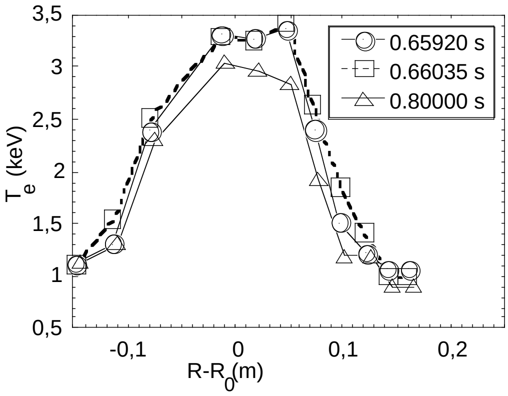

Fig.3- $T_e(r)$ profiles during island rotation

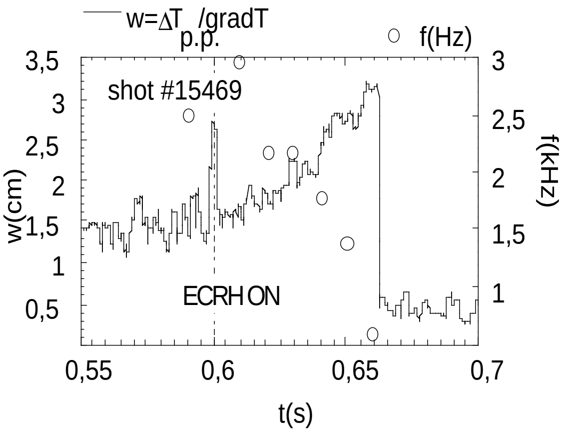

Fig.4- growth of "thermal" island width

The shoulder in the profile at the position where the largest thermal oscillations were observed shows that a magnetic island persists, although in a locked state. In fact the frequency of the oscillations lows down to locking during ECRH for shot #15469 (Fig. 4). In Fig. 5 a comparison is made of the observations with a theoretical model of the Rutherford [2] type. The model is obtained in the large R/a, RMHD ordering from the quasi-neutrality condition, Faraday and Ampere's laws averaged over the island and the momentum balance equation generalised to account for rotation, interaction with the resistive wall of radius r=d and toroidal coupling with modes of poloidal numbers $m, m\pm 1$:

$$\frac{dW_m}{dt} = \frac{r_m^2}{\tau_{R_m}}[\Delta'_m + C_{m,m\pm1}\frac{W_{m\pm1}^2}{W_m^2}\cos(\delta\phi) - f_R(\omega_m\tau_{wm})]$$

$$\frac{d\omega_m}{dt} = \frac{1}{I_\phi^{(m)}}[D_{m,m\pm1}W_{m\pm1}^2W_m^2\sin(\Delta\phi) - W_m^4 h_m^2 f_I(\omega_m\tau_{wm}) - \omega_m\frac{dI_\phi^{(m)}}{dt}] - \mu_{\perp m}\frac{r_m}{W_m}(\omega - \omega_m)$$

The non-linear function $\Delta'_m(W,\omega)$ is an effective stability index appropriately defined for each mode m including finite β_p terms [3,4]. $D_{m,m\pm1}$, $C_{m,m\pm1}$ are coupling coefficients consistent with momentum balance and $h_m = B r_{sm} q' / 16 R q^2$.The functions $f_R(\nu_m), f_I(\nu_m)$ represent the real and imaginary part of the wall response. to the time dependent magnetic perturbations $f(\nu_m) = \frac{2m}{r_{sm}} \left(\frac{r_{sm}}{d} \right)^2 \frac{(\nu_m)^2 + i\nu_m}{1 + (\nu_m)^2}$ for a circular large R/a geometry.

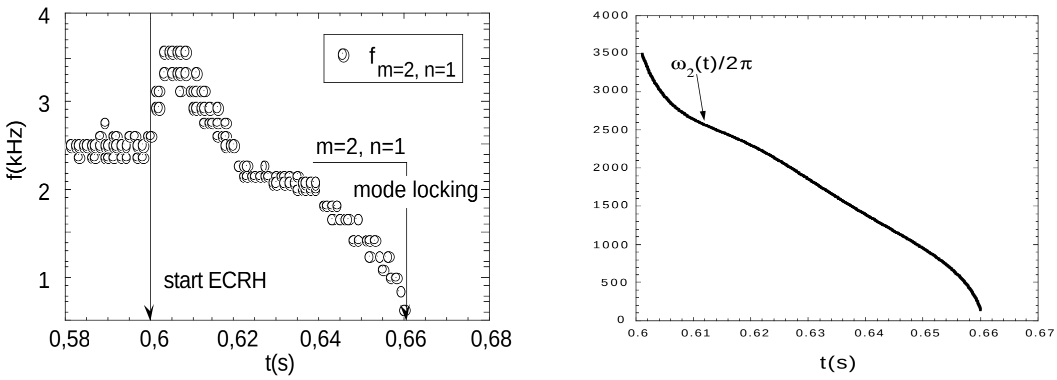

Fig.5-Experimental slowing down of rotation frequency $f_{2,1}(t)$ for FTU shot #15469 and theoretical model of d $f_{2,1}(t)$

These equations describe the role of the island inertia, the resistive wall braking torque and the electrodynamic coupling with the the m±1 sidebands. Coupling can have a stabilizing or destabilizing effect depending on the phase difference that evolves nonlinearly in a pendulum-like fashion. The onset of the mode is due to the the ECW heating effects of increasing $\beta_p(r_{q=2})$ close to the critical value for neoclassical tearing modes [3,4] $\beta_{p,crit}$~ 0.24 (Fig.6) and to partial reshaping of the J profile. The second case, is illustrated and reconstructed in Figs.7-9 (shot #14979). Before ECRH, periodic reconnections (sawteeth)

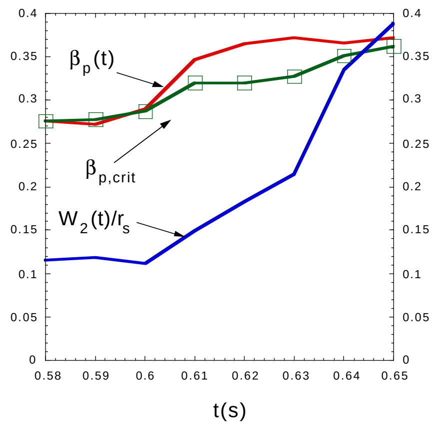

Fig.6 Time evolution of $\beta_p(t)$ and of W(t)

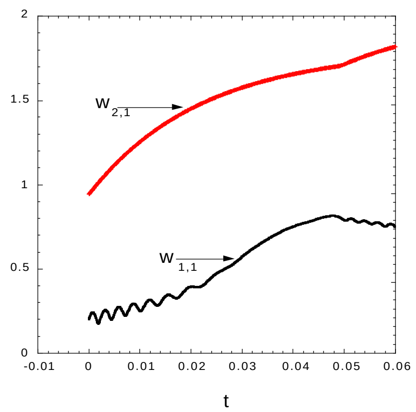

Fig.7- Theoretical model of evolution of the width width of copuled modes (2,1) (1,1) in shot #14979

During the ECRH pulse the (m=1, n=1) and the (m=2, n=1) modes are rotating tightly coupled, locked to a common frequency that jumps alternatively (e.g. at t~0.55s) between the m=1 and the m=2 natural frequencies $\omega_*(r_{q=1})/2\pi$ and $\omega_*(r_{q=2})/2\pi$ as a result of the competition between their mutual torque, the viscous drag and wall braking. The differentresponse of the wall drag to the two modes varies the phase shift between the modes altering their mutual torque. decorrelate the m=1,m=2 oscillations.

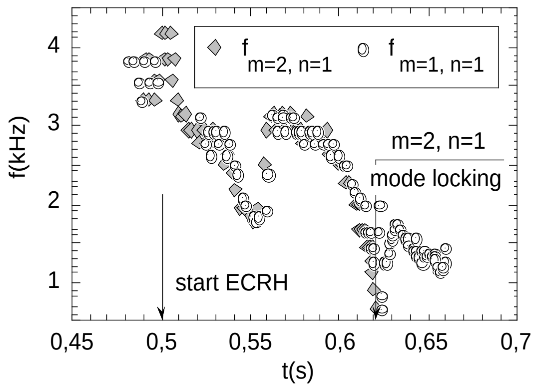

Fig.8- Evolution of the frequencies of the coupled modes therminating with locking of (2,1) and uncoupling of (1,1)

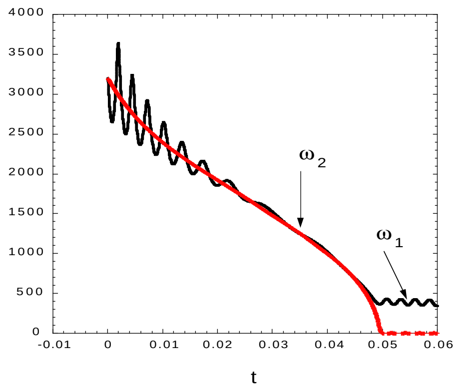

Fig.9-Numerical model of the case of Fig.8

When the viscous slowing down effect on the m=1 island nearly vanishes a large positive torque accelerates the m=2 island to the m=2 natural frequency $\omega_*(r_{q=2})/2\pi \approx 3\mathrm{kHz}$. Then through wall braking the m=2, n=1 mode is locked and the m=1 keeps rotating uncoupled and eventually decays in amplitude. The mechanism of unlocking is apparent from the equation ruling the evolution of the phase difference between the islands ;

$$\frac{d^2\Delta\phi}{dt^2} + aW_1^2W_2^2\sin(\Delta\phi) = d_1W_1^4 f_I(\omega_1\tau_{w1}) + d_2W_2^4 f_I(\omega_2\tau_{w2}) + \omega_1\frac{d\ln W_1}{dt} + \omega_2\frac{d\ln W_2}{dt}$$

where a, d_1, d_2 are constant coefficients.Unlocking occurs when $d_2 f_I(\omega_2\tau_{w2}) \approx aW_1^2W_2^{-2}$ The numerical results of the model show (Figs. 5-9) that the essential features of the experimental observations are identified.

Conclusions.

A comprehensive new experimental evidence and theoretical interpretation has been provided of paradigmatic cases, with relevant new physics concerning the mechanisms of magnetic island rotation and coupling conditions in a regime of tearing modes driven by increase of electron thermal energy and J profile reshaping.

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