26th EPS Conf. on Contr. Fusion and Plasma Physics, Maastricht, 14 - 18 June 1999 ECA Vol.23J (1999) 381 - 384

Internal m=1 mode and magnetic reconnection stabilization with off-axis ECRH at 800 kW on FTU tokamak

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Introduction

Experiments of localized ECRH/ECCD have been performed on the FTU tokamak for shaping the temperature/current density profile and controlling MHD activity. In particular, m=1 mode dynamics and stability have been studied during the heating phase, when the steady-state, sawtoothing conditions of the ohmic plasma are modified by a strong off-axis electron heating. Depending on the position of the absorbing layer and on the density of the ohmic target plasma, either sawteeth are temporarily suppressed, but a slowly growing m=1 oscillation persists, or a complete quenching of all m=1 activity can be achieved. When ECCD is added to the pure heating effect, various shapes and periods of relaxation phenomena in the plasma core are observed depending of the sign of the driven current. Although low values of I_{ECCD}/I_p are expected because of rather high values of Z_{eff} during heating, local changes in the magnetic shear are thought to be responsible of these differences. Here we consider the possibility that the observed very rapid variations in the sawtooth activity, may be due to local changes of the magnetic shear and the pressure gradient at the q=1 surface. Moreover a model is developed for the nonlinear regime of the m=1 mode dominated by magnetic shear and pressure modifications due to localized ECH power.

Experimental observations and sawteeth crash model

When the EC wave beams are launched perpendicularly to the toroidal direction and the main effect on sawteeth is due to localized heating, the sawteeth are modified as shown in Fig.1 [1]. If on-axis heating is applied, T_e rise is faster and sawtooth period decreases. On the contrary, stabilization can be achieved if the absorption layer r_{abs} is close to the sawteeth inversion radius r_{inv}. At this ECRH power level, however, stabilization is only temporary but at high density it can be complete. The following experimental features: i) internal relaxation oscillations are modified very rapidly after the EC-power turn-on time (in period, amplitude and shape), ii) the sensitivity to small changes of r_{abs} near r_{inv} suggest a model for sawtooth crash that depends on local modifications of the shear and pressure gradients at the q=1 surface. We consider first the linear regime to determine the plasma stability with respect to reconnection and, as a consequence, to simulate the sawtooth periods in FTU ECRH/ECCD discharges. The parameter range we considered ($n_e \approx 1 \times 10^{20}$ cm^{-3}, $T_e \approx 2 \div 5$ keV, $T_i \approx 1$ keV, $0.1 < s_1 < 0.5$) is that where $\rho_i > \delta_\eta > d_e$, where ρ_i is the ion Larmor radius, d_e is the inertial skin depth and $\delta_\eta = s_1^{-1/3} S^{-1/3} r_1$ is the resistive kink layer (S being the Lundquist number and s_1 the value of the magnetic shear at r_1 (the q=1 radius).

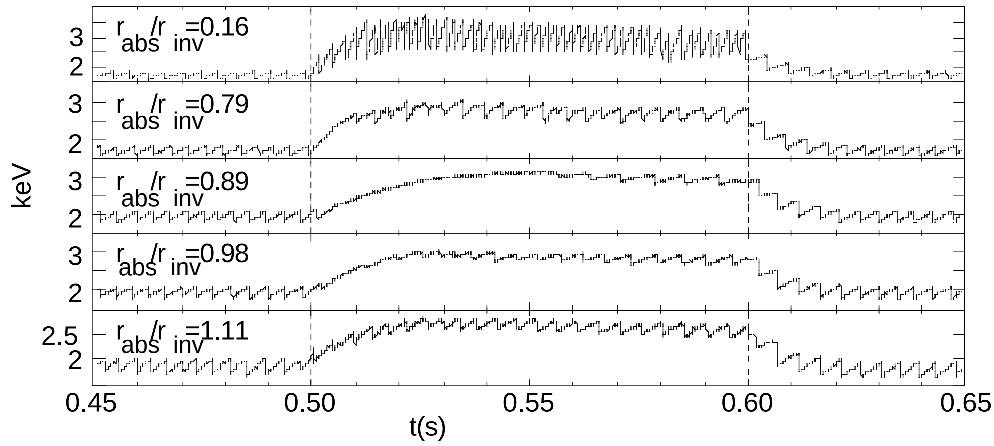

***FIG. 1.** Central electron temperature for different positions of the absorption layer r_{abs} with respect to the sawtooth inversion radius r_{inv}. The radii are computed at steady-state, accounting for Shafranov shift and q-profile modifications during ECRH. P_{ecrh}=800 kW; I_p=350 kA; P_{oh}=330->180 kW*

The inclusion of diamagnetic effects in the dispersion relation for the growth rate leads to a threshold for the sawtooth crash that can be translated in terms of a critical shear at the q=1 surface [2] :

$$s_1 \geq C^* \tau_A{}^{7/6} (\omega_{dia,e}\, \omega_{dia,i})^{7/12} (\pi T_i / 2(T_i + T_e))^{1/3} (r_1/\rho_i)^{2/3} (\tau_{res}/\tau_A)^{1/6} \qquad (2)$$

where all quantities are to be evaluated at the q=1 surface, $\tau_{res} = \mu_0 r_1^2 / 4\eta_0$ is the resistive time, τ_A is the Alfven time and $C^* \approx 1$. This condition (2) for the sawtooth crash was included in a 1-D transport code, in which the profiles are relaxed at the sawtooth crash according to Kadomtsev reconnection model [3]. The code allowed us to simulate with sufficient accuracy the sawteeth period also in cases where a co- or counter-current was driven by the EC waves near the q=1 surface.

ECRH control of non-linear m=1 mode

The typical response of sawteeth to ECRH (Fig.1) shows that transient stabilization can be immediately obtained as the ECRH is turned on (the central line in the figure) and later a finite amplitude non-linear m=1 mode appears. By applying ≈700 kW of ECRH power to a sawtoothing discharge at 350 kA, $q_a \approx 6$, $P_{ohmic} \approx 200$ kW, reconnections of the m=1 mode are frozen on a time scale of ≈25 ms, much shorter than the relevant resistive skin time scale and slowly growing m=1 oscillations at f≈10 kHz appear and eventually collapse after ≈ 30 ms (Fig.2). A possible explanation to the observed MHD behaviour may be given by a model of transition from the linear instability regime to a nonlinear one [4] dominated by the modifications of pressure gradient and resistivity caused by the localized ECH power.

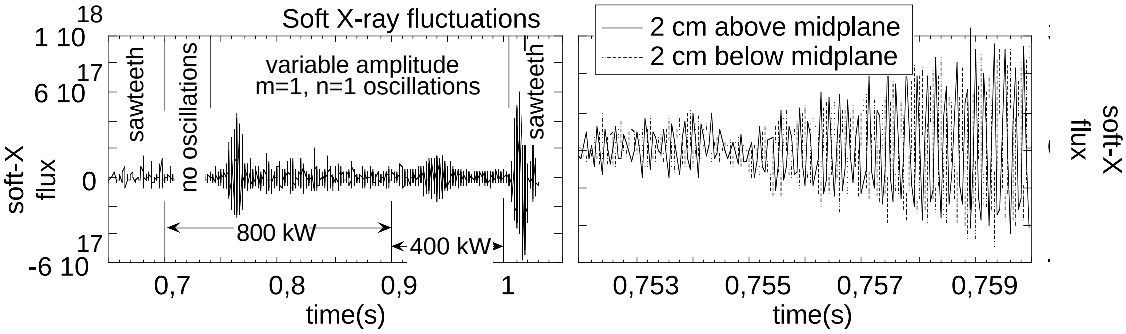

Fig.2. *Prompt stabilization lasts for ≈25 ms, << τ_{res} over the q<1 region. Coherent m=1 MHD oscillations with variable amplitude develop during the full ECRH pulse in shot #15536.*

This, in fact, has an impact on the structure and growth of the m=1 resistive mode through the changes of Pfirsch-Schlüter toroidal return current and of the magnetic shear [5]. The evolution of the amplitude of the Lagrangian displacement $\xi_0(t) = W(t)/2$ can be described symbolically by [5] $\dot{\xi}_0 = \gamma_L \xi_0 + \gamma_{NL}(\xi_0)\xi_0 + \gamma_I \xi_0$. The linear theory is valid for fluid displacements $|\xi_0| \le \rho_i (1 + T_e/T_i)^{1/2}$ and the nonlinear term $\gamma_{NL}(\xi_0)$ is meant to include and take over the linear one for large displacements [4]. The last term is the ideal kink growth rate, $\gamma_I \approx q'(r_s)\lambda_H \tau_A^{-1}/\sqrt{3}$, relevant for $\lambda_H = -(3\pi r_s^2 / q'R^2)(\beta_{crit}^2 - \beta_p^2) < 0$ [7]. The model developed here for the *nonlinear* stage is based on Maxwell's equations and a sufficiently general Ohm's law, in the RHMD description of fields in terms of flux and stream functions for the single helicity m=1 perturbation. It is assumed that q(0)<1 and a Rutherford type equation is deduced for a finite amplitude (displacement) m=1 mode [4-6]. A first element of the model is the assumed crescent-like structure of the m=1 helical flux contour $\Psi = -(B_0 s_1/2R)\{[x^2 - xW\cos\vartheta]H(-x) + x^2 H(x)\}$ related to the rigid displacement $\xi = (W/2)H(-x)\cos\vartheta$, where $x = r_1 - r$ [6]. The second element is the assumed expansion of the resistivity:

$$\eta(\Psi) = \eta_0 + \langle x \rangle \eta_0' + \delta t \dot{\eta}_0 = \eta_0 - \langle x \rangle \frac{3\eta_0}{2n_e T_e}[f'(r_1)\int_0^{\delta t} P_o^{EC}(\tau)d\tau] - \delta t \frac{3\eta_0 P_o^{EC} f(r_1)}{2n_e T_e}$$

where ECW heating has been taken *adiabatic* with a power density $P^{EC}(r,t) = P_o^{EC}(\tau)f(r)$. An analogous expansion holds for the pressure: $p(\Psi) = p_0 + \langle x \rangle p_0' + \delta t \dot{p}_0$. The EC driven perturbations of η and p modify the generalized Ohm's law $E_{//} = \eta J_{//} + \frac{4\pi}{\omega_{pe}^2}\frac{dJ_{//}}{dt} - \frac{1}{ne}\nabla p$ and the quasineutrality condition $\nabla \cdot \mathbf{J} = 0$. Combining these equations with Ampere's and Faraday law and integrating over the island region through the nonlinear operator $\Im(....) = \int_{-\pi}^{\pi} d\vartheta \cos\vartheta \int_{-\delta}^{0} (.....)dx$, one obtains the contributions in the reconnection process of all the competing and concurring electromotive forces. The result is an equation for the island width W and one for the rotation frequency heuristically deduced from momentum balance including an anomalous viscosity coefficient $\mu_{\perp}^{an}$:

$$\left(\frac{g_{rec}\tau_R}{r_1}\right)\frac{dW}{dt} = \{[1-\frac{(\alpha+\alpha_H(t))^2}{s_1^2}g_{PS} - g_h F_2(t)]\frac{r_1}{[W+g_d\frac{d_e^2}{r_1}]} - g_\eta[\frac{\eta_0' r_1}{\eta_0}+F_1(t)]\frac{W}{[W+g_d\frac{d_e^2}{r_1}]}\}$$

$$\frac{\partial\omega}{\partial t} = -\omega\frac{d\ln W}{dt} - \mu_{\perp}^{an}\frac{r_1}{W}(\omega-\omega_0)$$

where $F_1(t)$, $F_2(t)$ and $\alpha_H(t)$ are control terms dependent on the localized RF power pulse. The parameters $s_1 = q' r_1$ and $\alpha = 8\pi p' R/B^2$ are the local shear and normalized pressure gradient; the coefficients $g_{rec} \approx 0.3$, $g_{PS} \approx 1$, $g_h \approx 10$, $g_\eta \approx 6.3$ are obtained by non-linear averaging over the crescent-like m=1 island. The mode pulsation ω_0 is taken from the measurements. In Fig. 3 the model prediction of the m=1 fluctuations $\tilde{T}_{e,m=1}/T_e \propto \xi(t)$ are shown for the data of shot 15536. After turn-on of ECRH the width W approaches a saturation value inversely proportional to the absorbed power.

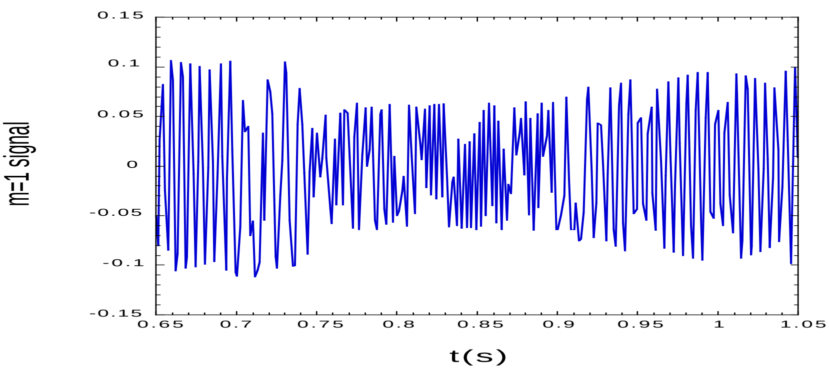

***Fig.3**. Qualitative reconstruction with the parameters of Fig.2, of the dynamics of the coherent and slowly growing m=1* $\tilde{T}_{e,m=1}/T_e$ *oscillations compressed by change of shear due to the ECRH pulse.*

As the plasma axis moves towards the resonance and r_1 increases, the shear s_1 increases violating again the linear stability criterion, the m=1 mode grows unstable and reconnection can take place again.

Conclusions

Experimental evidence and theoretical arguments support the view that the control of the magnetic shear at q=1 by local EC power is a crucial mechanism for the linear and non-linear behaviour of m=1 n=1 MHD perturbations.

[1] - S.Cirant, A.Airoldi, L.Bertalot, et al, *13th RF Conference*, Annapolis, 1999
[2] - Porcelli F. et al, *Plasma Phys. Contr. Fusion*, **38**, 2163, (1996)
[3] - G.Ramponi, A.Airoldi, A.Bruschi et al, *13th RF Conference*, Annapolis, 1999
[4] - L.E.Zakharov, F.M.Levinton, et al, *Fusion Energy 1994* **4**,407 (IAEA,1995)
[5] - A.I. Smolyakov , *Plasma Phys. Control. Fus.* **35**,657 (1993)
[6] - A.Thyagaraja, F.S. Haas, *Phys.of Fluids B* **3**,580 (1991)
[7] - M.N. Bussac et al, *Phys. Rev. Lett.* **35**,1638, (1975)