Modelling of NTM Stabilization by RF Heating and Current Drive in Plasma with a Stiff Temperature Profile

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Summary Neoclassical Tearing Modes (NTM) must be controlled or suppressed to prevent a degradation of the energy confinement for future devices. This can be done applying RF-current (ECCD) and -heating (ECRH) at the rational surface where the instability appears. The response of the plasma to a localised heating applied for the NTM control is sensitive to the stiffness of the temperature profile, behavior resulting from magnetised plasmas turbulent transport properties.[1] A new criterium for the minimum EC current required to stabilize an NTM is determined from a generalized Rutherford equation that includes heat. A lower ECCD current threshold is obtained when heat is considerd compared to pure ECCD criterion[7]. Background plasma heating decreases, however, the advantage of ECRH. Nonlinear simulations with the XTOR code [6] where a stiff plasma model and RF heating and current drive are implemented confirm the main properties of heating sources on saturation and stabilization, but also the moderate advantage of RF heating in the ITER case.

Turbulent transport model: We consider a simplify one parameter model for the stiff temperature profile $\chi_\perp = \chi_\perp^0 \left|T'/T'_{eq}\right|^{\sigma-1}$ [2] where $\chi_\perp^0$ is the perpendicular transport (heat diffusivity in the reference case), T_{eq} the equilibrium temperature, σ the stiffness parameter and T the temperature. Critical behaviors are obtained for σ values larger than unity. In ITER, a typical value at the q=3/2 resonant surface is $\sigma = 8$[3].

Modified Rutherford Equation We derive a stability criteria for NTM stability from a modified Rutherford equation including heat effects $dw/dt = a\Delta' + a\Delta'_{bs} + a\Delta'_{CD} + a\Delta'_\Omega$, with $a\Delta'_{bs}$ the destabilizing contribution due to bootstrap current, $a\Delta'_{RF}$ the stabilizing term due to ECCD and $a\Delta'_\Omega$ the heat source stabilizing term. The analytical form of the heat contribution $a\Delta'_\Omega$ for the heat transport model is given as $a\Delta'_\Omega = a\Delta'_\Omega(P_{RF} + \alpha_1 P^{res}_{eq}) - a\Delta'_\Omega(\alpha_1 P^{res}_{eq}) + a\Delta'_\Omega(P^{res}_{eq})$ $(\alpha_1 = 0.1)$ with:[2]

$$a\Delta'_\Omega(\hat{P}) = -(2\pi)^2 C_\Omega(\mu_c,\sigma)\,\frac{a}{\mathscr{J}}\frac{q}{s}\frac{\mu_0 R J_\Omega}{B_z}\left(\frac{\hat{P}}{P_{eq}}\right)^{1/\sigma}, \qquad (1)$$

where J_Ω the local ohmic current, $\mathscr{J} \approx rR$ the Jacobian, $\mu_c = (\delta_H/w)^2$, q the safety factor and $s = (r/q)dq/dr$ the magnetic shear at the resonant surface. In this model, $\hat{P}$ is the additional heat source centered at the O-point. This can either be ECRH (P_{RF}) or residual (P_{res}) heat

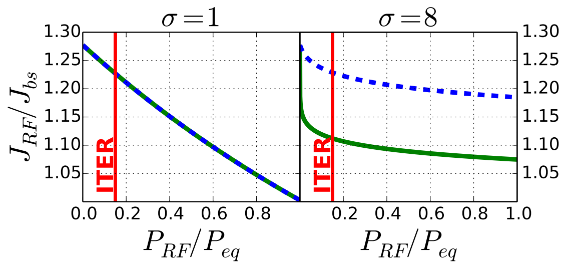

Figure 1: *Minimum J_{RF}/J_{bs} (Eq. (3)) required to stabilize the (3/2) NTM in ITER.*

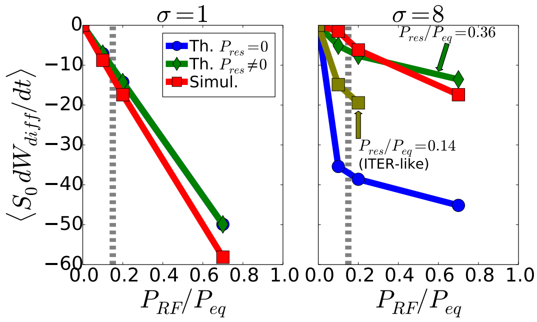

Figure 2: *Island decay rate due to the heating contribution with and without stiffness.*

source. Finally P_{eq} is the power injected inside the island position. The function $C_\Omega(\mu_c,\sigma)$ is approximated as (with $x \equiv \mu_c/\sigma$)

$$C_\Omega(\mu_c,\sigma) \approx \frac{3}{4\pi^2}\left[0.8+\frac{0.6}{\sigma}-1.09x+0.242x^2-0.228x\ln x\right]. \tag{2}$$

Key parameter $\hat{P}/P_{eq}$: The impact of heat to the NTM evolution is a function of $\hat{P}/P_{eq}$. In the case of no ECRH/ECCD, the NTM saturation size is decreased in presence of $P_{res} \propto w_s$ as $\bar{w_s} = w_s/(1+\widetilde{w})$, where $\widetilde{w}$ is a small perturbation due to residual heat. Considering that $P_{RF} \neq 0$, a condition for NTM stability when ECCD and ECRH are injected inside the NTM is

$$\left[1+w_s\frac{6.22}{L_T}\frac{J_\Omega}{J_{bs}}C_\Omega(x,\sigma)\left(\frac{P_{RF}}{P_{eq}}\right)^{1/\sigma}\right]\frac{\delta_{RF}}{w_s}\frac{J_{RF}}{J_{bs}}\eta_{RF} \geq \frac{1}{20.16}, \tag{3}$$

where J_Ω the equilibrium ohmic current density, J_{RF} is the ECCD current density and η_{RF} the ECCD efficiency[4]. Equation (3) demonstrates that the NTM stabilization by ECCD is facilitated when coupled to ECRH, i.e., less ECCD current is required as depicted in Fig. (1). This reduction is however limited for stiff plasmas and it typically saturates for $P_{RF}/P_{eq} > 0.2$. Residual heat sources further reduce the benefit of localised heating.

Neoclassical MHD Model: We use a simplified version of the ITER plasma equilibrium given in [5]. In particular, we remove the X-point and use up-down symmetric separatrix. We drive to saturation an NTM that sits on the rational surface q=3/2 of our ITER-like equilibrium. For that we solve the following set of non-linear normalized neoclassical MHD equations using the XTOR-2F code [6]

$$(\partial_t+\mathbf{V}_i\cdot\nabla)\rho = -\rho\nabla\cdot\mathbf{V}_i-\nabla\cdot\Gamma_{an}+S, \tag{4}$$

$$(\partial_t+\mathbf{V}\cdot\nabla)p = -\Gamma p\nabla\cdot\mathbf{V}-d_i\Gamma\mathbf{K}\cdot\left[\frac{p}{\rho}\nabla p_i+\frac{p_i}{\rho}\nabla p_i-\frac{p_e}{\rho}\nabla p_e+\frac{p_e^2-p_i^2}{\rho^2}\nabla\rho\right] \tag{5}$$

$$+H_{eq}-(\Gamma-1)\nabla\cdot\mathbf{q}_\chi+H_{RF}, \tag{6}$$

$$\rho(\partial_t+\mathbf{V}\cdot\nabla)\mathbf{V} = -\rho\mathbf{V}_i^\star\cdot\nabla\mathbf{V}_\perp+\mathbf{J}\times\mathbf{B}-\nabla p+\nabla\cdot\nu\nabla\mathbf{V}_i, \tag{7}$$

$$\partial_t \mathbf{B} = -\nabla \times \left[-\mathbf{V} \times \mathbf{B} + \eta \left[\mathbf{J} - \mathbf{J}_{bs} - \mathbf{J}_{CD} - \mathbf{J}_{RF} \right] - d_i \frac{\nabla_\| p_e}{\rho} \right], \tag{8}$$

with $\rho = n_i/n_i(0)$ the normalised mass density on axis, $\mathbf{V} = \mathbf{V_E} + \mathbf{V}_{\|,i}$, $\mathbf{V_E} = \mathbf{V} \times \mathbf{B}/B^2$, $\mathbf{V}_{\|,i}$ the ion parallel velocity, $\tau = T_e/T_i$, $d_i = V_A/(a\omega_{ci})$ the normalized ion skin depth, $\Gamma = 5/3$ represents the ratio of specific heat and $H = -(\Gamma - 1)\nabla \cdot \chi_\perp \nabla_\perp$ the heat source. The symbol H_{RF} represents the externally driven heat (ECRH). The diffusive heat flux is $\mathbf{q}_\chi = -\rho\chi_\| \mathbf{b}(\mathbf{b} \cdot \nabla T) - \rho\chi_\perp \nabla_\perp T$ models turbulent and collisional transport processes with $\chi\perp$ follows the simple stiff model described earlier ($\mathbf{b} = \mathbf{B}/|\mathbf{B}|$ and $T = p/\rho$). The particle source S restores the mass density profile, $\Gamma_{an} = (-D_\perp \nabla\rho + \rho \mathbf{V}_{pin})$ is the anomalous particle flux modelling the turbulent particle transport, $D_\perp = 2\chi_\perp/3$ the perpendicular diffusion coefficient and $\mathbf{V}_{pin}$ a pinch velocity. Both the heat source and particle sources are defined by their equilibrium profiles, they relax the profiles towards their equilibrium values. The current densities $\mathbf{J}_{CD} = \mathbf{J}\mid_{t=0}$, $\mathbf{J}_{bs}$, and $\mathbf{J}_{RF}$ are the current density source restoring the equilibrium current density profile, the bootstrap current and the current density externally driven (ECCD) respectively. The ECCD/ECRH are evolved by the following governing equations

$$\partial_t J_{RF} = \nu_f \left(J_s - J_{RF} \right) + \chi_\perp^{RF} |B| \nabla^2 \frac{J_{RF}}{|B|} + \chi_\|^{RF} |B| \nabla_\|^2 \frac{J_{RF}}{|B|}, \tag{9}$$

$$\partial_t H_{RF} = \nu_f \left(H_s^{RF} - H_{RF} \right) + \chi_\perp^{RF} \nabla^2 H_{RF} + \chi_\|^{RF} \nabla_\|^2 H_{RF}, \tag{10}$$

with $\mathbf{J}_{RF} = J_{RF}\mathbf{b}$ and ν_f the collision frequency of fast electrons. The subscript s denotes the source profiles.

NTM response to heating: Once the NTM reaches a saturated state for the stiffness parameter $\sigma = 1$, we compare the NTM evolution with $\sigma = 8$. The NTM saturated size that we obtain for our ITER-like equilibrium is about ten percents of the small radius, i.e., $w \approx 20$ cm. In addition, we compare for $\sigma = 8$ the default heat source $P_{res}/P_{eq} = 0.36$ with a peaked ITER-relevant heat source with $P_{res}/P_{eq} = 0.14$ [5]. Concerning the NTM decay rate, we perform a scan in the key parameter P_{RF}/P_{eq}. Because of residual heating, the advantage of ECRH is reduced in the case $\sigma = 8$ (see Fig. (2)).

Effective ECCD efficiency: Usually, the ECCD efficiency related to NTM decay rate is determined by η_{RF} without considering heat contribution [4, 7]. Here, we consider continuous and O-point modulated coupled ECCD/ECRH injections on the NTM for both $\sigma = 1$ and 8. The ECCD current is $I_{RF} = 0.8\% I_p$ with $I_p = 15$MA as given by the chosen ITER-scenario. Figure (3) shows the averaged values of an effective ECCD efficiency defined as

$$\eta_{eff} = -\frac{C_{CD}}{I_{RF}} w_s^2 \frac{dw_s}{dt}, \tag{11}$$

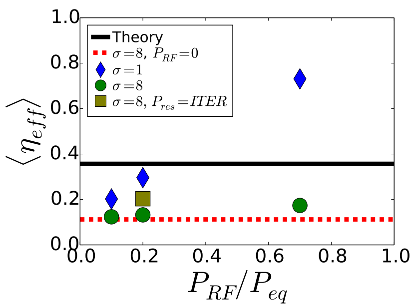

Figure 3: *Average effective stabilization efficiencies. Continuous injection.*

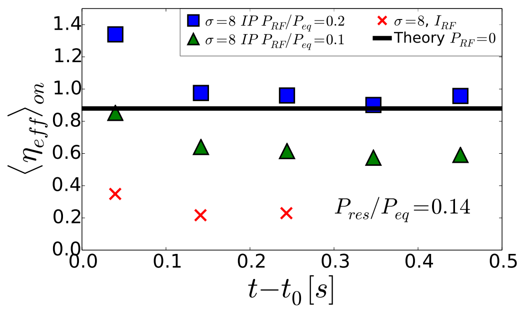

Figure 4: *Average effective stabilization efficiencies. Modulated injection.*

where C_{CD} is a geometrical constant. In such a way, we capture all the effects responsible for the NTM decay (including heating). We find that the time averaged effective ECCD efficiency $\langle \eta_{eff} \rangle$ is lower than theoretically predicted for a continuous pure ECCD injection[8]. For modulated injection, we average η_{RF} over the *on* time of the modulation cycle, i.e., when the RF antenna is firing at the NTM O-point. Figure (4) demonstrates that for a 50% modulated power, the stabilization efficiency is raised above the theoretical values of ECCD alone [6] for a ratio $P_{RF}/P_{eq} = 0.2$ (0.15 for ITER).

Conclusions: We demonstrated that the NTM evolution is affected by heating effects due to the stiff temperature profiles in tokamak plasmas. For that purpose, we derived a modified Rutherford equation for the NTM evolution that includes heating effects. We obtained that the NTM saturation size is reduced in presence of residual heat (no RF). Additionally, we deduced a criteria for the NTM stabilization showing that coupling ECRH to ECCD facilitate the island control. But, the presence of residual heat diminishes the advantage of ECRH. The role of heating on the NTM decay rate is emphasised for a large value of the key parameter P_{RF}/P_{eq}. Finally, we obtained that coupling ECCD with ECRH enhances the effective efficiency related to NTM decay rate. While the coupling is not sufficient to reach theoretical values derived for pure ECCD continuous injection, $\langle \eta_{RF} \rangle_{on}$ is closer the theoretical expectations for O-point modulation.

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