MODELLING OF THE NEO-CLASSICAL TEARING MODE AND ITS STABILISATION BY ECCD/ECRH

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1. Introduction and Computational Model

Neoclassical tearing modes (NTM)[1,2] often lead to a β-limit lower than that given by ideal MHD calculations or even to disruptions. Therefore, the understanding of the growth of nonlinear NTMs and the investigation of possible stabilising methods are very important. A straightforward method for suppressing NTMs is to drive an auxiliary non-inductive current in the o-point of the magnetic island in order to substitute the missing bootstrap current[3,4]. Due to its localised deposition, Electron Cyclotron Current Drive (ECCD) is most appropriate for this purpose. Here we use a numerical simulation to study the nonlinear growth and the saturation of NTMs and their stabilisation by phased ECCD and Electron Cyclotron Resonance Heating (ECRH).

Ohm's law and the equation of motion

$$\frac{\partial\psi}{\partial t} + (\mathbf{v}\cdot\nabla\psi) = -\eta(j_z - j_b - j_E) + E_0, \tag{1}$$

$$\rho\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla\right)\nabla^2\phi = \mathbf{e_z}\cdot(\nabla\psi\times\nabla j_z) + \rho\mu\nabla^4\phi, \tag{2}$$

are utilised, where ψ is the flux function defined by $\mathbf{B}=B_{0z}\mathbf{e_z}-(kr/m)B_{0z}\mathbf{e_\theta}+\nabla\psi\times\mathbf{e_z}$, $j_z=-\nabla^2\psi-2(n/mR)B_{0z}$ is the current density, ϕ is stream function defined by $\mathbf{v}=\nabla\phi\times\mathbf{e_z}$, and **B, v**, j_b and j_E denote the magnetic field, velocity, bootstrap current density and the driven current density by ECCD along the $\mathbf{e_z}$ direction, respectively. The subscript 0 denotes an equilibrium quantity, and m/r and k are the wave vector in $\mathbf{e_\theta}$ and $\mathbf{e_z}$ direction, respectively. The large aspect-ratio tokamak approximation (to the order $\sqrt{\varepsilon}$) is used.

$j_b = -g\frac{\sqrt{\varepsilon}}{B_\theta}\frac{\partial p}{\partial r}$ is calculated by solving the pressure evolution equation

$$\left(\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla\right)p = \nabla\cdot\chi_b\nabla_b p + \nabla\cdot\chi_\perp\nabla_\perp p + \frac{2}{3}Q, \tag{3}$$

where p is plasma pressure, χ_b and $\chi_\perp$ are the parallel and perpendicular transport coefficients, respectively, and Q is the heating power density. g is a function of the minor radius r depending on the collisional regime. For the transport coefficients $\chi_b=10^9a^2/\tau_R$ is taken. $\chi_b/\chi_\perp$ is taken as 10^8 at the magnetic axis, decreasing towards the plasma edge to 10^7. $\tau_R=a^2/\eta$ is the resistive time scale.

Assuming the location of the maximum driven current $\psi(r_E)$ to be located inside the magnetic island, the j_E profile is approximately symmetric on the two sides of the island´s o-point since the magnetic flux tubes on both sides of the o-point are connected inside the island. We describe j_E, therefore, by a Gaussian function of ψ,

$$j_E=j_{E0}\exp\left\{-2\left[\frac{[\psi - \psi(r_E)]}{[\psi(r_E) - \psi(r_E - w_E/2)]}\right]^2\right\}, \quad j_E=j_{E0}\exp\left\{-2\left[\frac{[\psi - \psi(r_E)]}{[\psi(r_E) - \psi(r_E + w_E/2)]}\right]^2\right\}, \quad (4)$$

for $r_E \leq r_o$ and $r_E > r_o$, respectively, where r_o is the location of the island´s o-point, j_{E0} and w_E are the magnitude of the driven current and the width of the current layer, respectively.

The change of plasma resistivity due to ECRH is taken into account assuming

$$\eta = \eta_0 + \tilde{\eta}\ , \qquad (5)$$

where η_0 indicates the influence of the magnetic island on the resistivity profile. Along a radial chord passing through the x-point η_0 is assumed to have the equilibrium value, whereas elsewhere it is calculated according to $\eta_0=\eta_0(\psi)$. The ECRH resistivity perturbation, $\tilde{\eta}$, is taken to have a Gaussian profile similar to Eq. (4). However, the minimum value of $\tilde{\eta}$ is at the o-point of the island rather than at $\psi(r_E)$ since we assume the power loss from the island to be dominated by heat conduction, making η a monotonic function of ψ inside the island.

2. Modelling Results

We first model the effect of NTMs on energy confinement, arising from the thermal shortcut of the energy flux through the island. In Fig. 1 the degradation due to a (3,2) NTM is shown as a function of the perturbed bootstrap current density, $fra=j_{b0}(r_s)/j_z(r_s)$. The dotted line gives the results of our numerical simulation whereas the solid line results from a linear theory for the island growth, and a linearised equation for the confinement degradation due to the magnetic island[5]. For a high fraction of bootstrap current one finds thereby a saturation at $\Delta\beta/\beta$=30% that is in good agreement with the experiment. This saturation is caused by a saturation of the island width for large bootstrap current rather than a saturation in the confinement degradation for large islands.

Next we model the stabilisation of NTMs by feedback-controlled ECCD and ECRH. Fig. 2 shows the saturated (3,2) magnetic island width as a function of the relative magnitude of the phased ECCD current for the case of $r_E=r_s$ and $w_E=0.1a$. Curve(a) is obtained with $\Delta\eta=0.0$, curve(b) with $\Delta\eta=0.05$, and curve(c) with $\Delta\eta=0.1$, where $\Delta\eta= \tilde{\eta}_0/\eta_0(r_s)$ is the normalised magnitude of the resistivity perturbation due to ECRH, and $I=I_E/I_p$ is the total driven current normalised to plasma current. The saturated island width decreases as I increases, and decreases further with additional ECRH for small driven current. However, the saturated island width does not become smaller than w/a=0.05 due to the finite current layer width w_E.

Fig. 3 shows the saturated magnetic island width as a function of We=w_E/a with $r_E=r_s$ and $\Delta\eta$=0.0. Curve(a) is obtained with I=0.005 and curve (b) with I=0.01. The saturated island width is approximately proportional to w_E.

As seen in Fig. 4 the effectiveness of the control current reduces if it is not driven exactly at the rational surfaces. The saturated island width is given here as a function of $\Delta\rho=(r_E-r_s)/a$ with w_E=0.1a. Curve (a) is obtained for I=0.005 and $\Delta\eta$=0.0, curve (b) for I=0.01 and $\Delta\eta$=0.0, and curve (c) for I=0.005 and $\Delta\eta$=0.1. For large islands, the best radial position for the ECCD current to reduce the island width is at 0.01a to the inside of the rational surface, since the o-point of the island is shifted radially inward from the original rational surface. As I and $\Delta\eta$ increase, the island and therefore, the shift of its o-point is small so that the best position of r_E for stabilisation is at the rational surface.

3. Discussions and Summary

Assuming the width of the deposition profile of electron cyclotron wave to be small, the width of the driven current profile is determined by $\tau_s=\tau_f$, where τ_s is the slowing down time of the fast electrons, $\tau_f=w_E^2/(4D)$ is the local confinement time of the fast electrons, and D is the diffusivity of the fast electrons. For this case

$$w_E = 2(D\tau_s)^{1/2} \propto T_{fast}^{3/4} D^{1/2} n^{-1/2}. \qquad (6)$$

For typical ASDEX-Upgrade parameter: $n=3\times10^{19}m^{-3}$, $D=1.0m^2/s$, and assuming the effective temperature of the fast electrons to be T_{fast}=15keV, Eq. (6) gives $w_E/a\approx 0.1$. Since w_E/a does not decrease much even for a large tokamak, the finite current layer width could be a limitation for a complete stabilisation of neoclassical tearing modes by ECCD for a reactor.

Assuming $\tilde{j}_b/j_{z0}<<1$ and $j_E/j_{z0}<<1$, the relative amplitude between the stabilising effect due to ECCD and due to ECRH on the island can be found approximately to be

$$R_{ECCD/ECRH}=\left|\frac{\eta_0\left[j_E(r_o)-j_E(r_x)\right]}{\left[\tilde{\eta}(r_o)-\tilde{\eta}(r_x)\right]j_{z0}}\right| \approx \frac{16\pi^2\gamma\kappa_\perp T_0}{3I_p c_j (w_E/a)(w/a)} \propto \frac{\kappa_\perp T_0^{5/4} n^{1/2} a^2}{D^{1/2} I_p w}. \qquad (7)$$

where $c_j= J_{z0}\pi a^2/I_p$, γ is current drive efficiency, and T_0 is the electron temperature. For typical ASDEX-Upgrade parameters one finds $R_{ECCD/ECRH}\approx 0.3$. For a tokamak reactor and a not too large island $R_{ECCD/ECRH}$ will be larger than one, so that phased ECCD will be more effective.

References

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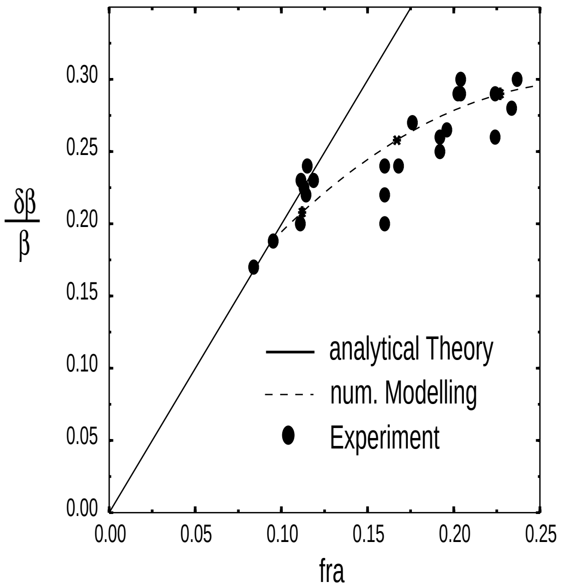

Fig.1 $\delta\beta/\beta$ versus the fraction of the bootstrap current density at the rational surface. For larger fra, $\delta\beta/\beta$ saturates at 30% caused by a saturation of the island width for large fra.

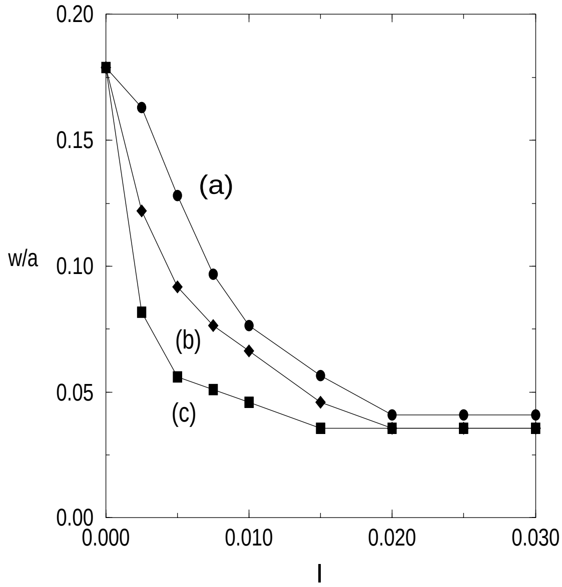

Fig.2 The saturated island width versus $I=I_E/I_p$, the relative amplitude of the driven current. Curve (a) is obtained with $\Delta\eta=0$, curve (b) with $\Delta\eta=0.05$, and curve (c) with $\Delta\eta=0.1$.

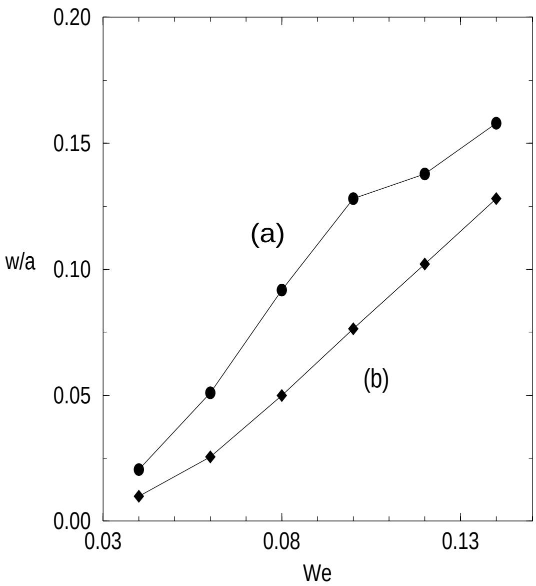

Fig.4 The saturated island width versus the width of the driven current for $r_E=r_s$ and $\Delta\eta=0$. Curve (a) is obtained with $I=0.005$ and curve (b) with $I=0.01$.

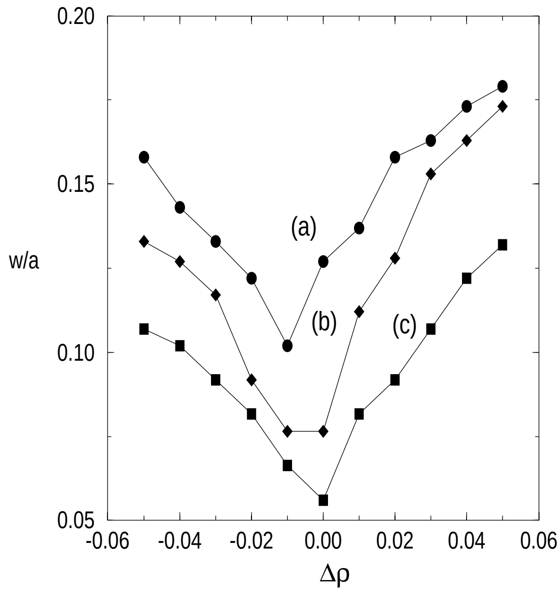

Fig.4 The saturated island width versus $\Delta\rho=(r_E-r_s)/a$. Curve (a) is obtained with $I=0.005$ and $\Delta\eta=0.0$, curve (b) with $I=0.01$ and $\Delta\eta=0.0$, and curve (c) with $I=0.005$ and $\Delta\eta=0.1$.