Neoclassical tearing modes: its locking by error fields and stabilization by RF current

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Abstract The locking of neoclassical tearing modes (NTMs) by error fields is studied. NTMs are found to be locked to low amplitude error fields in a fusion reactor. The stabilization of NTMs by RF current in the presence of a static helical field is further investigated. An applied helical field of a small amplitude to lock the island's o-point in the RF wave deposition region is found to increase the stabilizing efficiency.

1. Locking of NTMs by error fields

NTMs often lead to confinement degradation of tokamak plasmas or even to disruptions. Understanding the NTM physics and stabilizing NTMs are required for a fusion reactor [1-3]. The locking of NTMs by an error field is studied here numerically. The large aspect-ratio tokamak approximation is utilized. The magnetic field $\mathbf{B}=B_t\mathbf{e}_t-(kr/m)B_t\mathbf{e}_\theta+\nabla\psi\times\mathbf{e}_t$, where m/r and k=n/R are the wave vectors in $\mathbf{e}_\theta$ (poloidal) and $\mathbf{e}_t$ (toroidal) direction, R is the major radius, and m and n are the poloidal and toroidal mode numbers.

The Ohm's law, the equation of motion and the energy conservation equation are utilized. Normalizing the length to the minor radius a, time t to the resistive time $\tau_R= a^2\mu_0/\eta$, the helical flux ψ to aB_t, velocity $\mathbf{v}$ to a/τ_R, and electron temperature T_e to $T_e(r=0)$, one has

$$\frac{d\psi}{dt} = E-\eta(j-j_b-j_d) \tag{1}$$

$$\frac{dU}{dt} = -S^2\nabla_\parallel j+\mu\nabla_\perp^2 U+S_m \tag{2}$$

$$\frac{3}{2}n_e\frac{dT_e}{dt} = n_e\nabla_\parallel(\chi_\parallel\nabla T_e)+n_e\nabla_\perp(\chi_\perp\nabla T_e)+S_p \tag{3}$$

where $d/dt=\partial/\partial t+\mathbf{v}_\perp\cdot\nabla$, $j=\nabla_\perp^2\psi-2nB_t/(mR)$, $j_b=-c_b(r/R)^{1/2}n_eT_e'/B_\theta$ and j_d are the toroidal plasma current density, the bootstrap current density and RF driven current density respectively. η is the normalized plasma resistivity, E the equilibrium electric field, and $U=-\nabla_\perp^2\phi$ the plasma vorticity. $S=\tau_R/\tau_A$, $\tau_A=a/V_A$ is the toroidal Alfven time, μ the plasma viscosity, $\chi_\parallel$ and $\chi_\perp$ the parallel and perpendicular heat conductivities, S_p the heating power, S_m the poloidal momentum source, and n_e the electron density, The effect of the error field is taken into account by the boundary condition

$$\psi_{m/n}(r=a) = \psi_a a B_t \cos(m\theta+n\phi). \quad (4)$$

In figure 1 the required ψ_a to lock the m/n=2/1 island is shown as a function of the normalized island width w/a, with $S=10^8$, $\tau_\mu=a^2/\mu=0.01\tau_R$, $\chi_\perp=30a^2/\tau_R$, and $\chi_\parallel=3.0\times10^{10}a^2/\tau_R$. A monotonic profile for the safety factor q is assumed with the q=2/1 surface located at $r_s=0.727a$. Dedicated methods are utilized in the numerical code to reduce the numerical error [4]. The black circles (red squares) show the ψ_a for which the mode is locked (not locked). The different saturated island width results from different input values of the bootstrap current density fraction f_b. The slope of the curve shows that the required ψ_a for mode locking is proportional to $(w/a)^{-2}$, as the electromagnetic force applied on the magnetic island is proportional to the amplitude of the NTM.

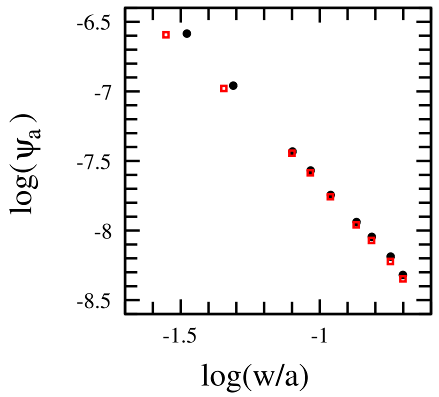

Fig.1 Mode locking threshold versus normalized island width w/a.

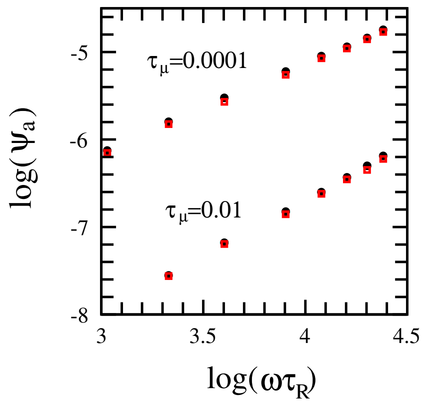

Fig.2 Mode locking threshold versus normalized mode frequency.

Figure 2 shows the mode locking threshold versus the normalized island angular rotation frequency $\omega\tau_R$ for two cases, $\tau_\mu=0.01\tau_R$ and $\tau_\mu=10^{-4}\tau_R$. The corresponding island width $w_s=0.156$ and 0.150a. The black circles (red squares) show the ψ_a for which the mode is locked (not locked). For $\tau_\mu=10^{-4}\tau_R$ the mode locking threshold is proportional to ω. As the electromagnetic force has to balance the plasma viscous and inertia forces, in the large μ (and/or low rotation speed) regime the viscous force dominates over plasma inertia, and it is found from Eq. (2) that the locking threshold is proportional to $\mu\omega V_A^{-2}$. For $\tau_\mu=0.01\tau_R$ the threshold increases slightly faster with increasing ω, showing the role of plasma inertia.

Above results indicate that the mode locking threshold of the m/n=2/1 mode is

$$\psi_a = c_{lock}\,\mu\omega(V_A w/a)^{-2}, \quad (5)$$

where μ is in the unit of m^2/s, V_A in m/s, and ω in s^{-1}. The parameter c_{lock} depends on the q-profile and the value of $\tau_\mu\omega$. In the low $\tau_\mu\omega$ regime $c_{lock}=17.0$ is found for the q-profile used here. While c_{lock}=28.8 is found for $\tau_\mu=0.01\tau_R$.

Equation (5) results from the reduction of the poloidal island rotation by the poloidal electromagnetic force. For the toroidal rotation case equation (5) is modified to

$$\psi_a = c_{lock}\,\mu\omega[(R/r_s)(m/n)]^2(V_A w/a)^{-2}. \qquad (6)$$

For a fusion reactor like ITER with B_t=6T, a=2m, R=6m, $n_e=5\times10^{19}m^{-3}$, $\mu=0.5m^2/s$, $w_{2/1}$=0.1a, $m_i=2m_p$, $r_{2/1}$=0.727a, and f=0.5kHz, the m/n=2/1 mode is found to be locked for ψ_a $=1.78\times10^{-6}$ with c_{lock}=28.8. It is seen that the NTMs will be locked by a small error field in a fusion reactor. Similar results are found for the m/n=3/2 mode [5].

2. Stabilization of NTMs by ECCD in the presence of a helical field

Once the island is locked at a particular toroidal and poloidal angle by the intrinsic machine error field, its o-point is not necessarily in the region covered by the RF waves deposition. A static helical field of an appropriate phase and amplitude can be used to ensure the island's o-point to be in the RF wave deposition region, so that the RF current can still play a stabilizing role after mode locking. This issue is investigated in the following.

To calculate the RF current density, the fast electron density is described by [5-7]

$$\frac{\partial n_f}{\partial t} = \nabla_\parallel(\chi_{\parallel f}\nabla n_f) + \nabla_\perp(\chi_{\perp f}\nabla n_f) + \upsilon_f(n_{fs} - n_f), \qquad (9)$$

where n_f, ν_f^{-1}, $\chi_{\parallel f}$ and $\chi_{\perp f}$ are the density, the slowing down time, the parallel and perpendicular transport coefficients of fast electrons. $n_{fs}=n_{fs0}\exp\{-[(r-r_{ds})/w_{ds}]^2\}\Pi(h_0)$ is the fast electron source due to the RF waves, where n_{fs0}, w_{ds} and r_{ds} specify the source magnitude, radial half-width and deposition radius. $\Pi(h_o)=1$ for $-\pi/2<\Delta h_o<\pi/2$, and $\Pi(h_o)=0$ elsewhere, describing the wave deposition along the helical angle $h=m\theta+n\phi$, where $\Delta h_o=(h_o-h_{RF})$, h_o is the instantaneous helical angle of the island's o-point, and the wave deposition is centered at h_{RF} with a width Δh. This leads to $\Pi(h_o)=1$ ($\Pi(h_o)=0$) when the island's o-point (x-point) is close to h_{RF}, corresponding to the modulated current drive (MCD). The helical field phase is chosen to lock the island's o-point at h=0. Assuming $j_d \sim n_f$, the RF current is obtained by integrating j_d over the plasma cross section. The RF source current I_{ds} is obtained similarly.

The saturated island width is shown by the solid line as a function of ψ_a in figure 3 obtained with f_b=0.226, h_{RF}=0, I_{ds}=0.03, Δh=0.482, and w_{ds}=0.04a. The straight dashed line shows the saturated island width w=0.059a obtained for ψ_a=0 (MCD). Without RF current the saturated island width w_s=0.23a for ψ_a=0. It is seen that the island width is smaller than that obtained with ψ_a=0 for $6\times10^{-7}<\psi_a<2\times10^{-4}$. In this region the island is locked by the helical field, and the stabilizing effect of the RF current is larger due to a two time larger RF current around the island's o-point. For $\psi_a>2\times10^{-4}$, the destabilizing effect of the helical field is too strong, leading to a larger island width than that obtained with $\psi_a=0$.

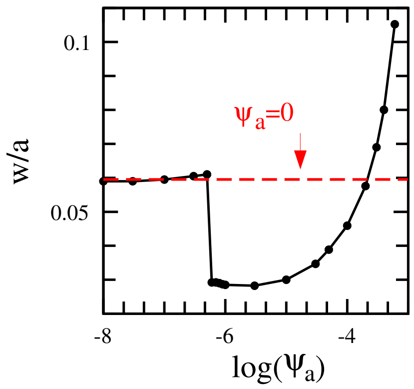

Fig.3 Island width versus the helical field amplitude at the edge.

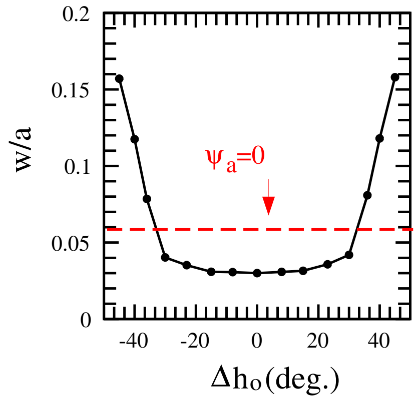

Fig.4 Island width versus the helical angle of the RF current.

Without an applied helical field to control the island phase, Δh_o is not necessarily to be zero after mode locking. In Fig. 4 the saturated island width is shown by the solid line as a function of Δh_o with $\psi_a=10^{-5}$. The enhanced stabilizing effect is limited for $\Delta h_o<30°$ (1/3 of the helical angle between the island's o-point and x-point). For a larger Δh_o the stabilizing effect sharply decreases, indicating the necessity of the island phase control.

It is seen that in addition to be able to control the island phase after mode locking to the intrinsic machine error field, the helical field can also be actively utilized to increase the NTM stabilization efficiency by RF current. Such a method is expected to be be useful for stabilizing large amplitude NTMs and avoiding disruptions caused by large locked islands in a fusion reactor.

In summary: (1) m/n=2/1 NTMs will be locked by a small amplitude error field in a reactor plasma. (2) An actively applied field for controlling the island phase is found to enhance the stabilizing effect of the RF current.

[1] O. Sauter, R.J. La Haye, Z. Chang, D.A. Gates, et al., Phys. Plasmas **4**, 1654(1997).

[2] H. Zohm, G. Gantenbein, G. Giruzzi, S. Günter, et al., Nucl. Fusion **39**, 577(1999).

[3] M. Maraschek, G. Gantenbein, Q. Yu, et al, Phys. Rev. Letts, **98** 025005 (2007).

[4] S. Günter, Q. Yu, J. Krüger, and K. Lackner, J. Comp. Phys. **209**, 354 (2005)

[5] Q. Yu and S. Günter, Nucl. Fusion **48**, 065004 (2008).

[6] Q. Yu, S. Günter, G. Giruzzi, et al., Phys. Plasmas **7**, 312(2000).

[7] Q. Yu, X.D. Zhang, and S. Günter, Phys. Plasmas **11**, 1960 (2004).