Stabilizing Effect of a Non-Resonant Helical Field on Neoclassical Tearing Modes

Q. Yu, S. Günter, K. Lackner

MPI für Plasmaphysik, EURATOM Association, D-85748 Garching bei München, Germany

It is found theoretically that once there are two neighboring neoclassical tearing modes (NTMs), the more unstable NTM suppresses the less unstable one, in agreement with the experimental results. The mechanism for the suppression is the decrease of the helical pressure perturbation of a NTM by the magnetic perturbation of another mode. Similarly, the NTM is found to be stabilized by an externally applied helical field of a sufficiently large magnitude with a different helicity, suggesting a possible method for stabilizing the NTM.

1. Introduction

NTMs have been found to limit the β value of tokamak plasmas and have therefore attracted much research efforts[1-4]. One issue regarding the NTMs is still of great concern: whether NTMs of different helicities driven by the pressure gradient can develop simultaneously in a tokamak reactor, leading to an enhanced transport or even to disruptions. As the β values for the mode onset is found to be proportional to the normalized ion Larmor radius ρ^*[5], in a reactor NTMs could occur for much lower β values than existing tokamaks.

In the present paper the interaction between NTMs is studied. It is found that whenever the amplitude of a m/n=2/1 mode becomes sufficiently large, the 3/2 mode decays due to the decrease of the 3/2 pressure perturbation by the 2/1 magnetic perturbation, where m and n are the poloidal and toroidal mode numbers, respectively. The numerical results agree with the experimental observations on ASDEX Upgrade[6]. Similarly, the NTM is found to be suppressed by an externally applied static helical magnetic field of a different helicity if the field amplitude is sufficiently large[7], suggesting a possible method for stabilizing NTMs in addition to the localized RF current drive[8].

2. Model

The basic equations describing the NTMs are Ohm's law, the equation of motion, and the pressure evolution equation,

$$\frac{\partial\psi}{\partial t}+\mathbf{B}\cdot\nabla\phi = E-\eta(j-j_b), \tag{1}$$

$$\rho\left(\frac{\partial}{\partial t}+\mathbf{v}\cdot\nabla\right)\nabla^2\phi = \mathbf{e}_t\cdot(\mathbf{B}\cdot\nabla j)+\rho\mu\nabla^4\phi, \tag{2}$$

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

where $\mathbf{B}=B_{0t}+\nabla\psi\times\mathbf{e}_t$ and $\mathbf{v}=-\nabla\phi\times\mathbf{e}_t$ are the magnetic field and velocity, and ψ and ϕ the magnetic flux function and the stream function, respectively. $j=-\nabla^2\psi$ is the current density along the $\mathbf{e}_t$ (toroidal) direction, $j_b=-g(\sqrt{\varepsilon}/B_p)dp/dr$ the bootstrap current density. g is a function of the minor radius r depending on the collisionality, $\varepsilon=r/R$ the inverse aspect ratio, B_p the poloidal field, ρ the mass density, μ the viscosity, p the pressure, Q the heating power, E the equilibrium electric field, and χ the transport coefficient. The subscripts b and $\perp$ denote the parallel and perpendicular components, respectively. B_{0t} is assumed to be a constant, and the bootstrap current is the only toroidal effect included.

3. Results

On ASDEX Upgrade NTMs of different helicities m/n=5/4, 4/3, 3/2, 2/1 have been observed, mostly coupled to an (m-1)/n kink mode. These NTMs, however, never occur simultaneously. They often appear as a sequence, starting with the mode of highest mode numbers. Such a sequence is shown in Fig. 1, in which the time evolution of the perturbed poloidal field amplitudes of the 3/2 and the 2/1 NTMs are shown. It is seen that, once the 2/1 mode is strong, the 3/2 mode decays.

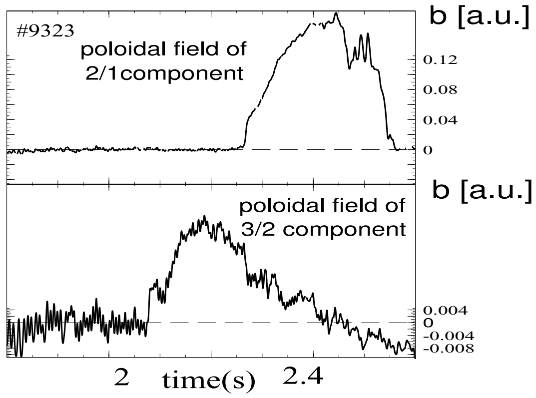

Fig.1 The time evolution of the 2/1 and 3/2 poloidal field amplitude, measured by Mirnov coils.

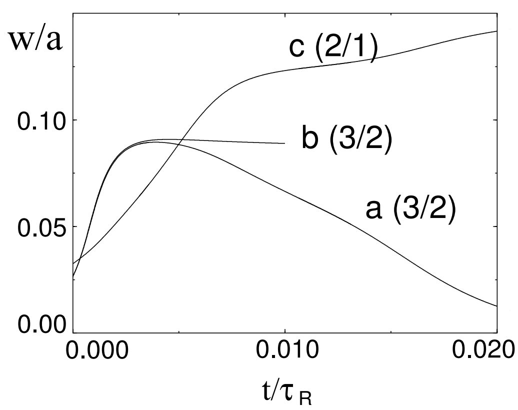

Fig.2 The time evolution of the island width of a 3/2 NTM with (curve a) and without (curve b) a 2/1 mode (curve c).

To understand the experimental results, Eqs. (1)-(3) are solved using an initial value code TM, which had been used to simulate the nonlinear growth of the single and double NTMs[9-11]. In the calculations, $\chi_b=2\times10^9a^2/\tau_R$, $\chi_\perp=24a^2/\tau_R$, and $S=\tau_R/\tau_A=5\times10^6$ are taken, where $\tau_A=a/v_A$, $\tau_R=a^2\mu_0/\eta$, and a is the minor radius. For the q-profile used, the distance between the rational surfaces of interest is approximately the same as the experimental one.

For a single m/n=3/2 mode, the time evolution of the normalized island width, $w_{3/2}/a$, is shown by the Curve b in Fig. 2. The q=3/2 surface is at $r_{3/2}=0.6a$ with a local bootstrap current density fraction $f \equiv j_{BS}/j_0=0.17$. The 3/2 island grows and saturates. If the 2/1 perturbation and the coupling between the 3/2 and the 2/1 modes are also included, keeping all the other input parameters unchanged, the time evolution of $w_{3/2}/a$ and $w_{2/1}/a$ are shown Curves a and c. The q=2/1 surface is at $r_{2/1}=0.725a$, and f=0.13 at $r_{2/1}$. It is seen that $w_{3/2}$ decays as $w_{2/1}$ becomes large. Numerical results also indicate that, the interaction between NTMs is stronger when their distance is smaller or their amplitudes are larger.

Analytical work has been carried out for understanding the numerical results[6,7]. The fundamental harmonic pressure perturbation of a NTM is found to be decreased when there is a helical magnetic field of a different helicity. This decrease leads to the corresponding decrease of the bootstrap current perturbation and therefore the drive of the NTM. Similar to Fig. 2, the 4/3 mode is found to be suppressed by the 3/2 mode.

Based on the results discussed above, the effect of a externally applied static helical magnetic field on NTMs is also investigated. For resulting in no magnetic islands inside the plasma and considering $\psi_{m/n}\sim r^m$ inside the plasma, it is desirable to select the field mode numbers to be m/n<1 with m=1 or 2. Here the effect of an m/n=1/3 helical field on the 3/2 NTM is studied numerically, by using the boundary condition $\psi_{1/3}(a)\neq 0$.

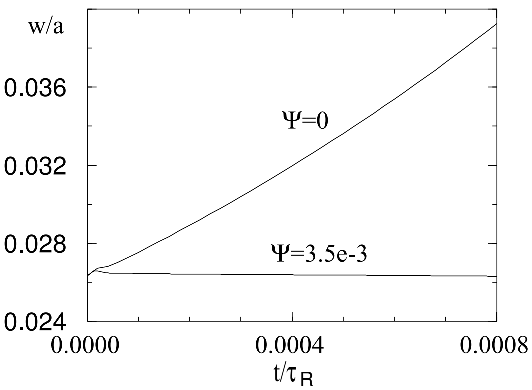

Fig.3 The time evolution of the normalized 3/2 island width with and without the m/n=1/3 helical field.

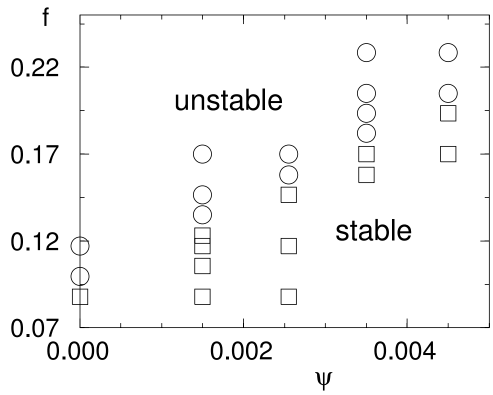

Fig.4 The required ψ for stabilizing the 3/2 mode. The squares (circles) denote the stable (unstable) cases.

In Fig. 3 the time evolution of the normalized m/n=3/2 island width is shown for $\Psi \equiv \psi_{1/3}(a)/a|\mathbf{B}_0|=0$ and $=3.5\times10^{-3}$, respectively, with f=0.17, $\chi_b=2\times10^8 a^2/\tau_R$, and $\chi_\perp=2.4a^2/\tau_R$. It is seen that w grows for Ψ=0 while decays for a sufficiently large Ψ.

The required amplitude of the 1/3 helical field for stabilizing the 3/2 mode is seen from Fig. 4 with w=0.26a at t=0, where the stable (squares) and unstable (circles) cases are shown in the Ψ-f plane. The required field amplitude Ψ is proportional to f. The magnitude of the transport coefficients can also affect the results to some extent.

In Fig. 5 it is shown that, the 3/2 island grows and saturates without the helical field but decays when the 1/3 field is turned on at t=0.005τ_R with Ψ=3.5×10^{-3} and 4.5×10^{-3}, respectively. The larger Ψ is, the faster the island decays. Using a nonlinear MHD code in toroidal geometry XTOR[12], the decrease of the 3/2 pressure perturbation amplitude by the helical field of a 2/1 mode is also observed (Fig. 6), in agreement with the results introduced above. In Fig. 6 the 3/2 pressure perturbations are taken with approximately the same 3/2 magnetic island width for the two cases, and $\psi_{2/1}$ is about 10 times lager than $\psi_{1/3}$ for Curve b.

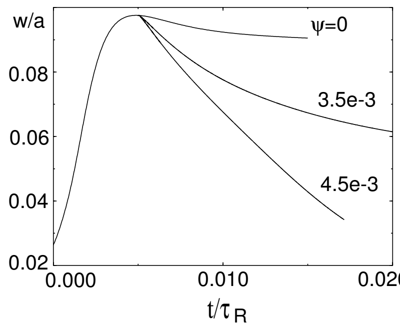

Fig.5 The time evolution of the normalized 3/2 island width with ψ=0, 0.0035 and 0.0045, respectively.

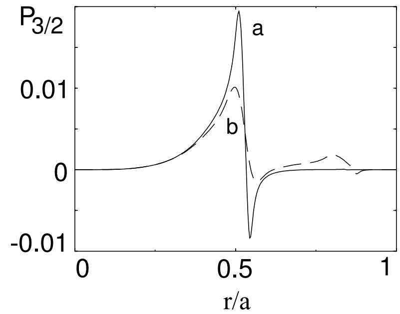

Fig.6 The 3/2 pressure perturbations without (a) and with the 2/1 mode and their couplings (b) from XTOR.

4. Summary

Once there are two neighboring NTMs, the less unstable one is found to be suppressed by the more unstable one, due to the decrease of the helical pressure perturbation of one NTM by the magnetic perturbation of another, in agreement with the experimental observations on ASDEX Upgrade. NTMs is also found to be stabilized by an externally applied static helical magnetic field of a different helicity, suggesting a possible simple method for stabilizing NTMs. For typical ASDEX Upgrade parameters, the required helical field amplitude for stabilizing the 3/2 mode is found to be less than one percent of the toroidal field.

Acknowledgment: We are grateful to M. Maraschek and A. Gude for checking the experimental results and to R. Arslanbekov and H. Lütjens for their help in using XTOR code.

[1] Z. Chang *et al.*, Phys. Rev. Letts, **74**, 4663(1995).
[2] H. Zohm *et al.*, Nucl. Fusion, **41**, 197(2001).
[3] R. J. La Haye *et al.*, Nucl. Fusion **37**, 397(1997).
[4] S. Günter *et al.*, Plasma Phys. Control. Fusion, **41**, B231(1999).
[5] S. Günter *et al.*, Nucl. Fusion **38**, 1431(1998).
[6] Q. Yu, *et al.*, Nucl. Fusion, **40**, 2031(2000).
[7] Q. Yu, S. Günter, K. Lackner, Phys. Rev. Letters, **85**, 2949(2000).
[8] H. Zohm *et al.*, Nucl. Fusion **39**, 577(1999).
[9] Q. Yu and S. Günter, Phys. Plasmas **5**, 3924(1998).
[10] Q. Yu and S. Günter, Nucl. Fusion **39**, 487(1999).
[11] Q. Yu, S. Günter *et al.*, Phys. Plasmas **7**, 312(2000).
[12] H. Lütjens and JF. Luciani, Phys. Plasmas **4**, 4192(1997).