Theory of Neoclassical Tearing Modes and its Application to ITER

V.D. Pustovitov 1), A.B. Mikhailovskii 1), N. Kobayashi 2), S.V. Konovalov 1),
V. S. Mukhovatov 3), A.V. Zvonkov 1)

1) Russian Research Centre “Kurchatov Institute”, Moscow, Russia
2) ITER Garching Joint Work Site, Garching, Germany
3) ITER Naka Joint Work Site, Naka-machi, Naka-gun, Ibaraki-ken, Japan

e-mail contact of main author: pustovit@nfi.kiae.ru

Abstract. Neoclassical tearing modes (NTM) can be responsible for beta limitation in long-pulse ITER discharges. The excitation and growth of NTM are governed by the competing bootstrap current, polarization current and so-called Δ' effects. Also, the magnetic well and Electron Cyclotron Current Drive (ECCD) can stabilize the NTM. We study analytically and numerically all the effects with a particular emphasis on the polarization current in the analytical part of our study. We show that the polarization current description requires a generalized transport theory including the hyperviscosity, electron pressure gradient and, as well, the finite ion Larmor radius effects in the perpendicular current. The profile function nonstationarity must be taken into account for calculation of the island rotation frequency. Results of numerical simulation of NTM suppression by modulated ECCD in ITER are presented.

1. Introduction

Neoclassical tearing modes (NTM) are considered as one of the most serious potential limitations on the attainable plasma pressure in long-pulse tokamak discharges. Existing theories and available data (yet incomplete and insufficient for conclusive predictions) give unfavourable scalings for larger devices. Thereby, the physics of NTM is an important area for ITER [1].

Existing theory of NTM is based on the generalised Rutherford equation for the time evolution of the width W of the magnetic island (see, for example, [2-4]):

$$\frac{\tau_s}{r_s}\frac{dW}{dt} = r_s\Delta'(W) + \beta_p\left[\frac{C_b W}{W^2+W_0^2} - \frac{C_{mw}}{W} - \frac{C_p}{W^3}\right] - \frac{C_{CD}}{W}. \qquad (1)$$

Here $\tau_s = \mu_0 r_s^2/(1.22\eta)$ is the resistive time at the resonant surface of radius r_s, η is the neoclassical resistivity, Δ' is the conventional tearing parameter, β_p is the poloidal beta at the resonant surface, W_0 is the characteristic island width below which the cross-field transport dominates over parallel transport and equilibrates the pressure along the island, the term with C_b accounts for the destabilizing neoclassical bootstrap drive, the term with C_{mw} is related to the stabilizing effect of the magnetic well, the term with C_p describes the effect of so-called polarization currents induced by the diamagnetic motion of the island through the plasma, and the last term with C_{CD} is associated with the stabilizing effect of properly localised current drive.

NTM theory provides us more or less reliable expressions for C_b, C_{mw} and C_{CD}. However, the value and even sign of C_p are still under discussion. One of the goals of our study is analysis of the polarization current contribution into Eq. (1). Another goal is optimisation of ECCD stabilization of NTM in ITER-FEAT, which is modelled using Eq. (1).

2. Collisionality Dependence of NTM

Both theory and experiment show that C_p depends on the ion-ion collision frequency ν_{ii}. The standard form of the coefficient C_p in Eq. (1) is [2,3,5]

$$C_p = a_{pol} r_s g(\varepsilon,\nu_{ii})(\rho_p L_q / L_p)^2, \qquad (2)$$

where a_{pol} is the constant (usually considered as positive, of order unity), ε is the local inverse aspect ratio of the resonant surface, ρ_p is the poloidal ion Larmor radius, $L_q = q/q'$ and $L_p = -p/p'$ are the shear and pressure gradient scale lengths, and g is the factor describing the collisionality dependence of the polarization current effect.

The term with C_p is stabilizing provided that $C_p > 0$. Its amplitude depends on ν_{ii} through function g of which the asymptotics are 1 in the collisional neoclassical MHD limit $\nu_{ii}/\varepsilon\omega > \varepsilon^{-3/2}$ [6] and $\varepsilon^{3/2}$ in the regime of weakly collisional kinetics $\nu_{ii}/\varepsilon\omega < 1$ [7], where ω is the island rotation frequency in the plasma rest frame of reference.

Theory of magnetic islands is not yet developed for the interval $1 < \nu_{ii}/\varepsilon\omega < \varepsilon^{-3/2}$. However, the theory of linear MHD instabilities allows to obtain the expression [8]

$$g = \frac{\nu_{ii}^2 + \omega^2\varepsilon^{1/2}}{\nu_{ii}^2 + \omega^2/\varepsilon}. \qquad (3)$$

It was assumed earlier that $g = 1$ for $\nu_{ii}/\varepsilon\omega > 1$ [7]. Later it was found that experimental data could be explained in the polarization current model with $g = 1$ in the range $\nu_{ii}/\varepsilon\omega > 0.3$ [2] and even for $\nu_{ii}/\varepsilon\omega > 0.03$ [5]. This obviously contradicts expression (3), see Fig. 1. The contradiction can be explained by the fact that all theoretical models are simplified, and a better theory is needed to interpret the experimental data. Also, it is desirable to study the role of different factors determining the behaviour of NTM, such as equilibrium electric field in a plasma and interaction of NTM with a resistive wall.

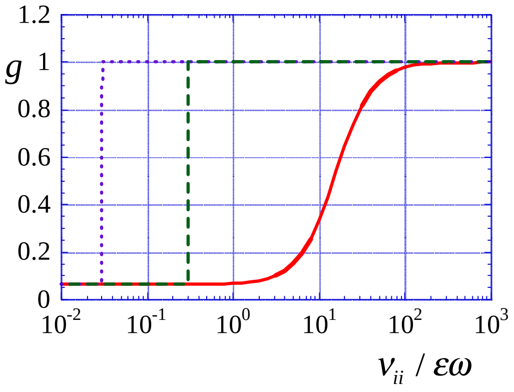

FIG. 1. Function $g(\varepsilon,\nu_{ii})$ *for* $\varepsilon = 0.16$. *The bold line corresponds to Eq. (3). The dashed line illustrates the dependence proposed in [2]. The dotted line shows the function proposed in [5].*

3. Is Polarization Current Stabilizing or Not?

The concept of recent models of NTM that the polarization current is stabilizing goes back to theoretical calculations of [7]. Later it was proposed to revise this concept by including the contribution of the polarization current from the near-separatrix region [9]. This would reverse the sign of the polarization current contribution in the generalised Rutherford equation making this contribution destabilizing in the absence of diamagnetic drifts [9] (for superdrift magnetic islands, SDMI).

Recent analysis [10-12] confirmed the conclusion of [9] that the polarization current destabilizes SDMI. However, analysing drift magnetic islands, DMI, one should deal with several profile functions characterising spatial dependence of the perturbed electric field, plasma density and electron and ion temperature. Within such an approach in the simplest case of uniform equilibrium temperature we obtain

$$C_p \propto -(\omega - \omega_{*i})(\omega + k_* \omega_{*i}) , \tag{4}$$

where ω_{*i} is the ion drift (diamagnetic) frequency, and k_* is a positive number. The approach of a common profile function [7] leads to (4) with $k_* = 0$. For $k_* = 0$, the polarization current can be stabilizing only for islands propagating in the ion drift direction if their rotation frequency is smaller than the ion drift frequency, $0 < \omega / \omega_{*i} < 1$. Meanwhile, the calculations of [7] predicted only the islands propagating in the electron drift direction, $\omega / \omega_{*i} < 0$. For $k_* = 0$ this means that [7] would predict the destabilizing polarization current, with agreement with the mentioned conclusion of [9]. However, according to Eq. (4) even for $\omega / \omega_{*i} < 0$ the polarization current can be stabilizing if the island rotation frequency is sufficiently small.

It is necessary to analyse whether assumption $\omega / \omega_{*i} < 0$ is correct by considering, besides the so-called $E_{\|}$-mechanism [7], such mechanisms affecting the island rotation frequency as perpendicular and neoclassical viscosity. They are related to the ion dissipation, so a proper theory should predict the islands propagating in the ion drift direction. According to [13], one should take into account that viscosity depends on gradients of the velocity and the ion heat flux. Then one can find that even for $k_* = 0$ the polarization current is stabilizing.

4. Numerical Simulation of NTM Suppression by Modulated ECCD

Results of the numerical simulations of NTMs and their suppression by modulated ECCD are presented for ITER-FEAT plasma with $\beta_N = 1.77$, $n_e = 10^{20}$ m^{-3}, $T_e(q = 3/2) = 7.11$ keV, $T_e(q = 2/1) = 4.41$ keV and $Z_{eff} = 1.67$, with a gyrotron frequency of 170 GHz. ECCD current density in the vicinity of the resonant surfaces have been calculated using the ray-tracing and Fokker-Planck code OGRAY [14]. Equatorial and upper port launching schemes were considered to optimise the efficiency of the ECCD stabilization system. The launching angles were chosen so as to keep the power deposition on the magnetic surface $q = 2$ ($q = 1.5$). NTM evolution was described by the equation (1) with values of C_b, C_{mw}, C_p, C_{CD} used in [3,15] and $\Delta' = m / r_s$. The value $g(\varepsilon, \nu_{ii})$ was taken to be 1 for 2/1 mode and $\varepsilon^{3/2}$ for the 3/2 mode. The saturated width W is $0.14a$ for the 2/1 mode, the seed island width determined by the polarization term is $0.025a$, where a is the effective minor radius.

We considered two kinds of NTM island suppression, as illustrated in Fig. 2. For suppression of the saturated island the right hand side of Eq. (1) must be negative for all values of the island width. The detection of the island and application of ECCD on the early stage of island development allows its suppression by smaller EC power, but this possibility crucially depends on the polarization term and needs detailed theory of the polarization current effect.

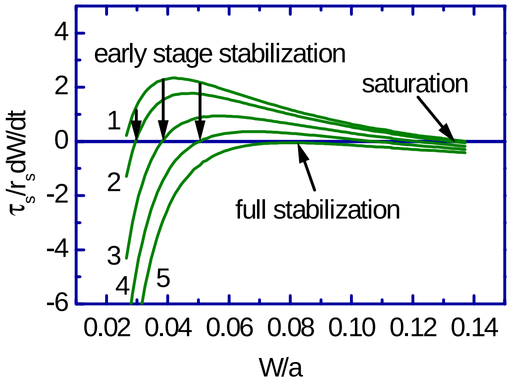

FIG. 2 The right hand side of the generalized Rutherford equation (1) as a function of the normalised island width W/a for different EC power values, $P_5>P_4>P_3>P_2>P_1=0$.

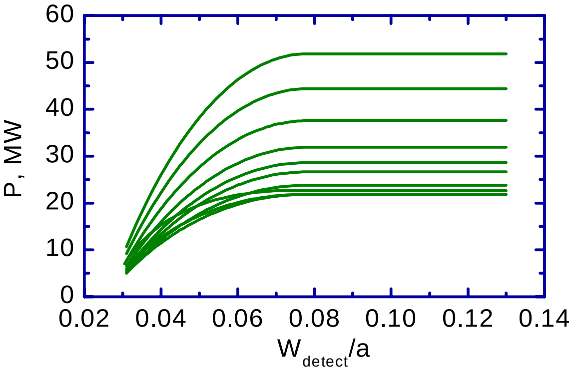

FIG. 3 Necessary EC power as a function of the island detection size for upper launching with angles between the wavebeam and the poloidal plane (launching angles) in a range 11-29^0. The minimal power for $q=2$ case is obtained for angles between 23^0 and 26^0.

For equatorial launching the total power required to stabilize both 3/2 and 2/1 saturated NTM islands in ITER FEAT was found to be 35 MW (with CD efficiency η_{20}(2/1)=0.045 and η_{20}(3/2)=0.085 $Am^{-2}W^{-1}$). The optimal toroidal inclination (more exactly, the angle between the launching direction and the poloidal plane) was about 21-22^0 in this case. For upper launching the total power was found to be 28 MW (η_{20}(2/1)=0.062 and η_{20}(3/2)=0.10). The optimal toroidal inclination is about 24-26^0. Approximately 80% of EC power is spent to stabilize $m/n=2/1$ mode, the other 20% on $m/n=3/2$. Comparison of the two launching schemes shows that the upper port launching seems more preferable for NTM suppression.

Necessary power may be lower if islands of small width can be detected. Figure 3 shows the dependence of EC power necessary for NTM stabilization as a function of the island detection size. For a larger detection size only full stabilization is possible, and the necessary power is constant, but for small enough detection size the required power is smaller. In particular, if ECCD starts at $W/a=0.04$, the total power required for suppression of the islands for the upper launching scheme reduces to 18 MW, for equatorial launching to 22 MW.

It should be noted, however, that the above estimates of ECR power requirements are obtained with simplified expressions for the terms in Eq. (1), derived for circular, large aspect ratio plasma. Preliminary modeling of plasma shaping effect on the magnetic well term C_{mw} (still in the large aspect ratio approximation) and stabilizing effect of ion temperature gradient in the bootstrap drive C_b demonstrated rather favourable tendency: decreasing the size of saturated $m/n=2/1$ and 3/2 islands and resulting decrease in the ECR power for their suppression. For considered ITER scenario the stabilizing magnetic well contribution C_{mw} was found to be comparable with the destabilizing bootstrap drive ($C_{mw}/C_b \approx 0.5$ and 0.8 for $m/n=3/2$ and 2/1 modes, respectively), i.e. more important than it was expected earlier [3]. This gave us more than twofold reduction in the stabilizing ECR power needs. Further developing of the numerical code with geometrical and other improvements of the model and its benchmarking against available experimental data is necessary for more reliable predictions for ITER.

5. Summary

The polarization current term in Eq. (1) substantially affects the NTM behaviour diminishing the value of EC power necessary for NTM suppression, especially on the early stage of the island evolution. Therefore, reliable expressions for this term are highly desirable. Our future study will be aimed at this problem, as well as at more accurate calculation of other terms in the equation of NTM evolution in tokamaks with non-circular plasma.

There are grounds for a hope that in the case of DMI the polarization current stabilizes NTM. However, at some conditions not DMI, but SDM islands can be excited. According to [12], the reason for SDMI excitation can be a combined effect of the strong equilibrium electric field in a plasma and the wall resistivity. In this case polarization current can be destabilizing.

Modeling of NTM with customary definitions of the terms in Eq. (1) shows that 28 MW of EC power is sufficient to suppress saturated $m/n = 2/1$ and $3/2$ islands in ITER-FEAT and EC power can be reduced to 18 MW if smaller islands ($W/a \sim 0.04$) can be detected.

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