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Effect of plasma rotation on neoclassical tearing modes in ITER

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1. Introduction

Effect of sheared plasma rotation on MHD stability of neoclassical tearing modes (NTM) in ITER are investigated using the nonlinear three-dimensional magnetohydrodynamic (MHD) code NFTC [1]. One of the major scenario in ITER where NTM problems should be significant is the inductive regimes with $\beta_N = 1.8$ and resonances m/n = 3/2 and 2/1 within the plasma. External helical magnetic fields of different configurations are included in the model enable studies of stability control problems and error fields problem in creating the seed island for NTM excitation. The effect of nonlinear coupling of different toroidal tearing modes in the presence of external helical fields on MHD stability is examined.

2. Basic equations in the NFTC model

The nonlinear 3D evolution of a tokamak plasma is described by the full non-reduced, compressible, MHD system of equations which include viscosity, resistivity and sources. The equations are formulated in general toroidal geometry. We seek the solution $\mathbf{Y} = \{\mathbf{V}, \mathbf{B}, \mathbf{P}\}$ of the full MHD equations, with the velocity $\mathbf{V}$, magnetic field $\mathbf{B}$, and pressure P. The functions $\mathbf{B_{eq}}(\rho,\theta)$ and $P_{eq}(\rho,\theta)$ describe the initial axisymmetric solution of the equilibrium equations. An arbitrary function $\mathbf{V_{eq}}(\rho,\theta)$ describes the initial plasma rotation velocity.

The basic equations then take the following form:

$$\overline{\rho}\frac{\partial \mathbf{V}}{\partial t} = -\overline{\rho}((\mathbf{V_{eq}}+\mathbf{V})\cdot\nabla)(\mathbf{V_{eq}}+\mathbf{V}) - \nabla\mathbf{P} + [[\nabla\times(\mathbf{B}+\mathbf{B_{ex}})]\times(\mathbf{B}+\mathbf{B_{ex}})] + \nu\nabla^2\mathbf{V} \qquad (1)$$

$$\frac{\partial \mathbf{B}}{\partial t} = [\nabla\times[\mathbf{V}\times(\mathbf{B}+\mathbf{B_{ex}})]] - [\nabla\times(\eta[\nabla\times(\mathbf{B}+\mathbf{B_{ex}})])] + [\nabla\times\mathbf{E_s}]; \qquad (2)$$

$$\frac{\partial P}{\partial t} = -\nabla\cdot(P(\mathbf{V_{eq}}+\mathbf{V})) - (\Gamma-1)[P(\nabla\cdot((\mathbf{V_{eq}}+\mathbf{V}))] + \nabla_\parallel\cdot(K_\parallel\nabla_\parallel P) + \nabla_\perp\cdot(K_\perp\nabla_\perp P) + Q; \qquad (3)$$

Note that in these equations, density $\overline{\rho}$ is assumed to be constant(unity). In these dynamic equations $K_\perp, K_\parallel, \eta, \nu$ and Q are dimensionless values of the perpendicular thermal conductivity,finite heat conductivity along perturbed magnetic surfaces,resistivity, the kinematic viscosity and heat source term. The following are the sources of current density: the bootstrap current j_{BS},the ECCD current j_{cd},the current from neutral beam injection j_{NB}, the polarization current j_{pol}, the Ohmic current density j_Ω. The total parallel current density is the sum of Ohmic current and the non-inductive current: $j = j_\Omega + j_{\mathrm{BS}} + j_{\mathrm{cd}} + j_{\mathrm{NB}},$. Then $E = \eta j_\Omega = \eta j - E_s$, where the source term is included as $E_s = \eta(j_{\mathrm{BS}} + j_{\mathrm{cd}} + j_{\mathrm{NB}})$. The bootstrap current j_{BS} is included in the simplest model form: $j_{\mathrm{BS}} = 1.46\sqrt{\varepsilon}[-\frac{\partial P/\partial \rho}{B_{\mathrm{pol}}}]$. Current densities j_{cd}, j_{NB} and j_{pol} are omitted in the present study.

$\mathbf{B_{ex}}(\rho,\theta,\varphi)$ is the external helical magnetic field which satisfies the equations inside plasma volume:

$$[\nabla \times \mathbf{B_{ex}}] = \mathbf{0} \tag{4}$$

$$(\nabla \cdot \mathbf{B_{ex}}) = \mathbf{0} \tag{5}$$

and the boundary conditions on the surface Σ for normal component of magnetic field:

$$\mathbf{B}_\perp|_\Sigma = \sum_{mn} B^c_{mn} cos(m\theta - n\phi) + B^s_{mn} sin(m\theta - n\phi) \tag{6}$$

Coefficients B^c_{mn}, B^s_{mn} permit us to consider different external helical fields configurations. In this report we consider the fields of two configurations. In first configuration we take m/n=1/1 as the basic harmonic. All other harmonics will be present at calculations due to the shaped toroidal geometry of plasma and will be smaller in amplitude. Plasma evolution with such field configuration hereinafter called as Hm1 regime (high m=1). In the second configuration we take m/n=2/1 as a basic harmonic and amplitudes of other harmonic will be small. Simulation with this field configuration hereinafter called as Lm1 (low m=1) regime.

Metric elements $g_{ik}(\rho,\theta)$ are calculated corresponding to the straight field line coordinate system ρ,θ,φ using $(\mathbf{B}_{\mathrm{eq}}, P_{\mathrm{eq}})$, where $\rho = \sqrt{\psi_N}$ is a radial-like coordinate which labels to the magnetic surface, θ is a poloidal-like angle, and φ is the toroidal angle.

3. Effects of external helical magnetic fields and plasma rotation on NTMs excitation.

Inductive scenario 2 for ITER was under the study where the basic equilibrium corresponds to $\beta_N = 1.8$. Fig.1 shows the islands n=2 evolution when plasma rotation and external magnetic fields are not included in calculations. Long time development of the basic 3/2 mode corresponds to the model resistivity $\eta = 10^{-7}$. For ITER we have $\eta = 10^{-10}$ and real time will be much longer. Found threshold is equal to $W/a = 0.005$. Maximum island width is equal to $W/a = 0.07$. All other toroidal modes are small in this case.

Fig.2 shows the stabilizing effect of plasma rotation on the 3/2 mode for different resistivities: $\eta = 10^{-6}$, $\eta = 5\cdot 10^{-7}$, $\eta = 10^{-7}$. Horizontal line corresponds to the seed island $W/a = 0.0125$ for the 3/2 mode. The mark “ ITER” corresponds to the toroidal plasma rotation in the scenario 2 when the frequency in the center is equal to 1 kHZ. It is seen that due to small resistivity and small growthrates of tearing modes in ITER, the value of plasma rotation planed in the scenario 2 is quite enough for stabilization.

Calculations show that the effect of the external helical magnetic field on the NTMs excitation strongly depends on the presence of the m/n=1/1 component in field representation. The set of calculation with different magnitudes of the 2/1 magnetic field in the Lm1 regime is shown in fig.3. The dependence of the magnetic islands 2/1 and 3/2 on the magnitude of the 2/1 magnetic field $\mathbf{bex} = \frac{\mathbf{B}^{\rho}_{\mathbf{2/1}}}{B_{\phi 0}}$ component on the plasma boundary is presented. Plasma rotation corresponds to 1kHz in the center. In this Lm1 regime we have the situation when the 2/1 island is stable for all values of magnetic field. It is seen that the 3/2 island stabilizes by the 2/1 field harmonic in this case. In the reasonable range of the 2/1 field the influence on the 3/2 mode when $\beta \sim 1.8$ is small. Fields of the 4G order doesn't excite the 2/1 NTM. The mark "ITER" corresponds to the error fields of the $\mathbf{bex} = 0.3 \cdot 10^{-4}$ order which could be corrected.

In the Hm1 regime the stability situation is absolutely different. Calculations show that the main reason for that is the strong influence of the m/n=1/1 component on the tearing modes interactions. Fig.4 shows the comparison of the time evolution of magnetic islands in Hm1 and Lm1 regimes. Even the small 2/1 magnetic island could be excited as the NTM mode in the Hm1 case. Also the interaction of the basic modes 3/2,1/1,4/3,2/1 leads to instability of the 4/3 and 3/2 mode. Growthrates of the forced reconnection are much faster in the Hm1 regime.

Effect of plasma rotation on modes excitation in the Hm1 regime is presented in fig.5. The time evolution of the m/n =2/1,3/2,4/3 modes is shown for two different frequencies of rotation in the center: ω_0 (basic rotation) and $2.0 \cdot \omega_0$. It is seen that if the rotation is twice increased, the 3/2 mode stabilizes, but the 2/1 and 4/3 modes destabilize.

Pressure perturbation in the Hm1 regime is presented in fig.6.

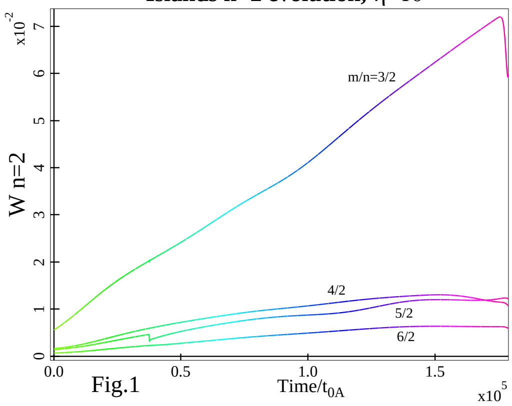
4. Conclusions.

Calculations show that NTMs instability could be excited by external helical fields in the presence of toroidal rotation. Toroidal rotation stabilizes the 3/2 mode in the scenario 2 with no error fields. It is found that two external helical magnetic fields configurations are different in respect of instability excitation. When the 1/1 component of field is large, then instability situation could be dangerous for ITER. To avoid strong instability due to error helical fields in ITER it is needed to correct the m/n =1 component of helical fields of the 3G order.

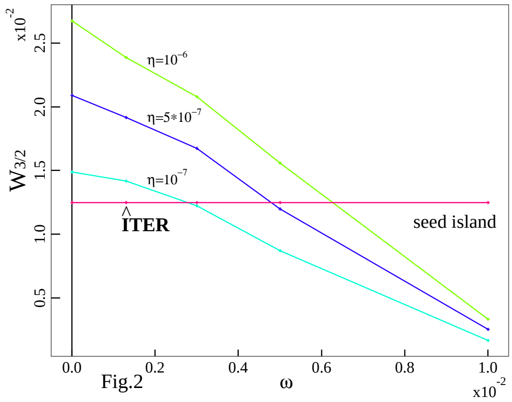
References

[1] A.M.Popov et al. Physic of Plasmas, **l9**, 10 (2002),p.4205

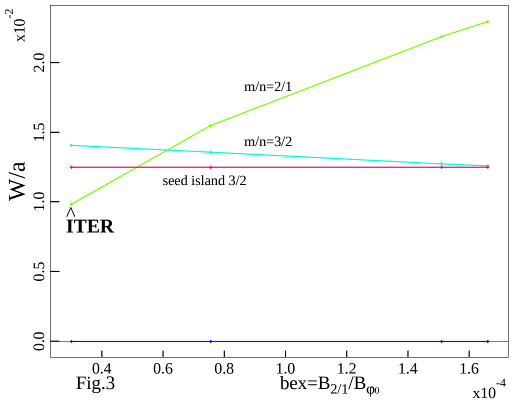
Islands n=2 evolution, $\eta=10^{-7}$



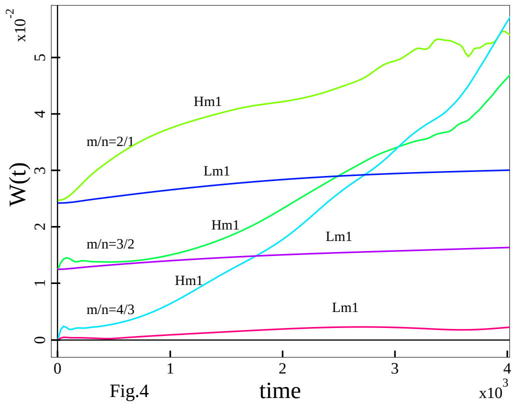
Effect of rotation on 3/2 mode in ITER



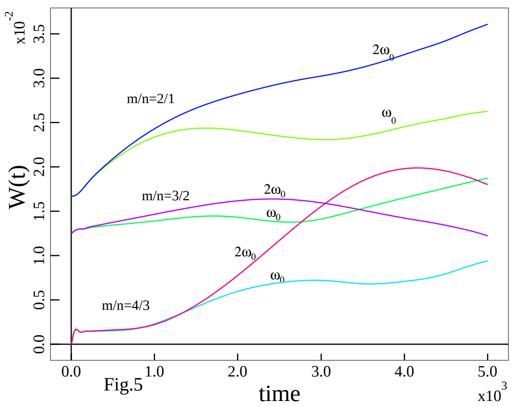
Effect of external fields m/n=2/1 on 3/2 NTM



Islands evolution in Hm1 and Lm1 regimes



Efect of plasms rotation on islands in Hm1 regime



Pressure perturbation