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3D SIMULATIONS OF NEOCLASSICAL TEARING MODES IN ITER

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1. Introduction

Nonlinear self-consistent MHD stability simulations of nonlinear interaction of different neoclassical tearing modes (NTMs) in ITER is investigated using the nonlinear three-dimensional magnetohydrodynamic (MHD) code NFTC [1-3]. There is one of the major scenario in ITER where NTM problems should be significant: inductive regimes with$\beta_N \sim 2$ and resonances m/n = 3/2 and 2/1 within the plasma. For ITER the required magnitude of radially localized electron cyclotron current drive (ECCD) for full NTMs suppression is high and the CD location with respect to the rational surface needs to be very accurate. The present work is directed to analysis of the possibilities to reduce the requirements for ECCD using the nonlinear interaction of MHD modes with different helicities. Frequently Interrupted Regime (FIR) obtained in ASDEX Upgrade [4] is one of the possible scenario.In this regime (m/n) NTMs are characterized by frequent amplitude drops caused by interaction with (m+1,n+1) background MHD activity and lower confinement degradation is found compared with usual NTMs [4]. The regimes with strong nonlinear modes coupling in ITER , maximum island width and effect on confinement with different ECCD power are analysed using 3D simulations.

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:

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

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

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

and an equation of state which is taken to be adiabatic $\frac{d}{dt}(\frac{P}{\bar{\rho}^{\Gamma}}) = 0$ Note that in these equations, density $\bar{\rho}$ 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 aer the sources of current density: the bootstrap current $j_{\rm BS}$,the ECCD current $j_{\rm cd}$,the current from neutral beam injection $j_{\rm NB}$, the polarization current $j_{\rm pol}$, the Ohmic current density j_{Ω}. The total parallel current density is the sum of Ohmic current and the non-inductive current: $j = j_{\Omega} + j_{\rm BS} + j_{\rm cd} + j_{\rm NB},$. Then $E = \eta j_{\Omega} = \eta j - E_s$, where the source term included as $E_s = \eta(j_{\rm BS} + j_{\rm cd} + j_{\rm NB})$. The bootstrap current $j_{\rm BS}$ is included in the simplest model form: $j_{\rm BS} = Ag \cdot 1.46\sqrt{\varepsilon}[-\frac{\partial P/\partial\rho}{B_{\rm pol}}]$. Current density j_{cd} we represent as a radially localized toroidal current of perturbed helical magnetic flux. In NFTC code we use the following simplified form

$$j_{\rm cd} = I_{\rm cd}(t\|W)\frac{1}{2\pi^{3/2}W_{\rm cd}}\{e^{-(\rho-\rho_{cd})/W_{\rm cd}^2} \cdot (1 + \frac{1}{8}(\frac{W_{mn}}{W_{\rm cd}})^2 \cos(m\theta - n\varphi + \alpha\pi))\} \quad (4)$$

Here W_{mn} is the magnetic island width.
Metric elements $g_{ik}(\rho, \theta)$ are calculated corresponding to the straight field line coordinate system ρ, θ, φ using $(\mathbf{B}_{\rm eq}, P_{\rm eq})$, 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. NTMs interaction in the presence of ECCD current. Inductive scenario 2 for ITER was under the study and basic equilibrium corresponds q(0)=0.97 and $\beta_N = 1.8$. Modeling the sawtooth ramp period we change q(0) from 1 to 1.07. First we study the NTMs coupling with no ECCD to understand the effect of the natural background activity on 3/2 NTM instability. Calculations show that there is no strong nonlinear interaction of basic modes 1/1, 3/2, 4/3 in this case.

To excite 4/3 mode instability we use ECCD for current profile modification and increase β_N from 1.8 to 2.3. The deposition of ECCD current ρ_{cd} was chosen between rational surfaces of two modes $\rho_{4/3}$ and $\rho_{3/2}$. In this case we have the modification of equilibrium current profile in a such a way that the magnetic shear becomes smaller near 4/3 surface and larger near 3/2 surface. Fig.1 shows the time dependence of magnetic islands after ECCD switching on. It is seen that 3/2 mode becomes stable. At the same time there is the 4/3 and 1/1 modes excitation. With different parameters there is the situation when 4/3 and 1/1 instability leads 3/2 mode suppression. Evolution of 3/2 and 4/3 modes with no ECCD is shown for comparison. In this case instability of 3/2 leads to the decaying of 4/3 and 1/1 mode. There is the moment of time (critical-point) in nonlinear evolution, when q profile after local modification, starts the fast relaxation to initial equilibrium profile and the instability of 3/2 mode appears again. There is the maximum of quasilinear correction of equilibrium profile in the critical-point of evolution due to unstable helical modes. This effect determines the start time to the fast relaxation. Maximum level of 3/2 islands depends on the time of q-profile modification. Note the large 4/3 and 1/1 modes amplitude when 3/2 mode stabilizes.

Fig.2 shows the effect of CD magnitude $i_{cd} = I_{cd}/I_p$ on island evolution. The time dependencies of m/n=3/2 and m/n=4/3 islands are shown for different values of ratio $i_{cd} = 0.00625; 0.0125; 0.025; 0.0333$. Saturation island will be of order $W = 0.025a$ (0.05m) even for $i_{cd} = 0.0125$ which is twice less than for the case of exact deposition at rational 3/2 surface.Nevertheless soft relaxations are exists in this case and amplitudes of 4/3 and 1/1 modes are not so big. So, it is possible to have the instability of 3/2 mode in some controllable level which is lower than the saturation level.

The trigger of instability leading to the strong nonlinear interaction of modes and fast relaxation is the sensitive issue for ITER. The time period of relaxation depends on the type of mode excited in the critical-point. Fig.3 shows the radial velocity profiles for basic modes m/n=1/1,3/2 an 4/3 after 3/2 suppression. It is seen that in the period of 3/2 stabilization the level of 1/1 and 4/3 perturbation is large. Mode 1/1 has ideal internal kink mode structure located inside $\rho_{4/3}$ surface and 4/3 have resistive kink structure. Both modes have large growth rates. Pressure perturbations connected with mostly 1/1 and 4/3 modes are presented in fig.4. Pressure gradients become large in the area of small shear near 4/3 surface. It is difficult to have conclusion that 4/3 mode is an ideal infernal mode, because its growth rate (although is large due to reduced shear), depends on resistivity. For ITER the 4/3 mode growth rates will be reduced in comparison with simulation prediction. Also, the reduction of resistivity results in the increasing time period of relaxations.

The effect of accuracy of ECCD deposition $\Delta\rho = \rho_{cd} - \rho_s$ on 3/2 mode stabilization is also important for ITER . Fig.5 shows the time dependence of islands width with different deposition $\Delta\rho = \rho_{cd} - \rho_{3/2}$. It is seen that exits some area between rational surfaces of 4/3 and 3/2 mode where 3/2 mode suppression is most preferable. In opposite, CD deposition on the 3/2 magnetic islands boundaries increases the instability. Fig6 shows the effect of j_{cd} deposition on maximum island width Wmax/a with $i_{cd} = 0.025$. Close to rational surface 3/2 mode is completely suppressed. At rational surface $\rho_4/3$ the m/n=4/3 mode is suppressed and we have no influence on 3/2 mode instability. Shown area between rational surfaces where 4/3 mode is large is most preferable for 3/2 suppression. Accuracy of ECCD deposition is twice less than for complete 3/2 mode stabilization near q=3/2 surface.

4. Conclusions.

Self-consistent calculations using the NFTC code show the effectiveness of ECCD suppression of neoclassically destabilized magnetic islands of 3/2 mode in the presence of nonlinear modes 1/1,4/3,3/2 coupling.

With no ECCD the interaction of the modes are small for equilibrium profiles. ECCD leads to modification of current profile creating strong modes coupling.

With reducing CD power it is possible to enter to soft stationary state with slowly growing 4/3 mode and decaying 3/2 mode. Calculations show that ECCD could be reduced using nonlinear modes coupling. For Icd/Ip =0.0125 (Icd=0.188MA for Ip=15MA) which corresponds 20MW power gives $W_{max} = 0.05m$ after entering of controllable nonlinear coupling regime.

The accuracy of ECCD deposition can be slightly reduced in comparison with full suppression of mode. But it is still needed to coincide the large pressure gradients with low magnetic shear near 4/3 surface.

References

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m/n=3/2 and m/n=4/3 evolution when q_min=1.07

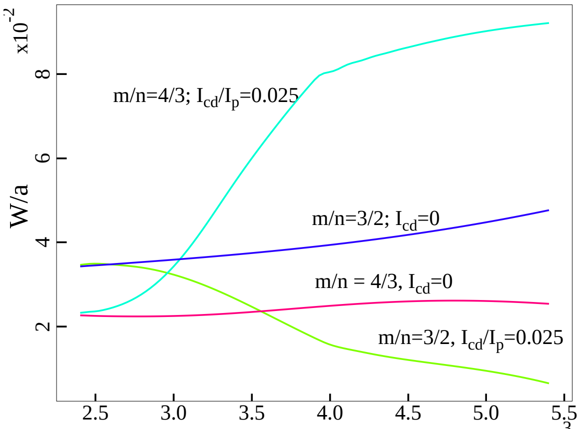

Fig.1

Effect of i_cd = Icd/Ip on islands evolution

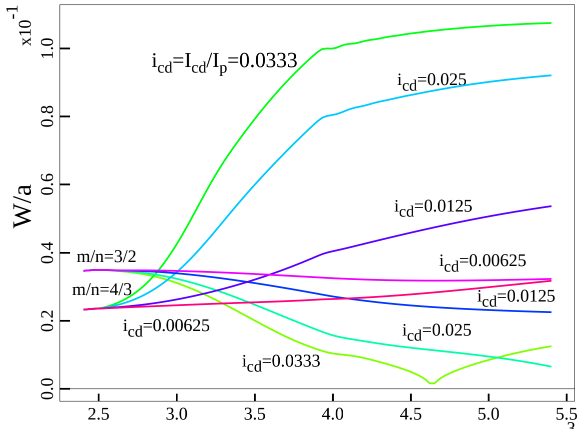

Fig.2

Radial velocity after m/n=3/2 suppression

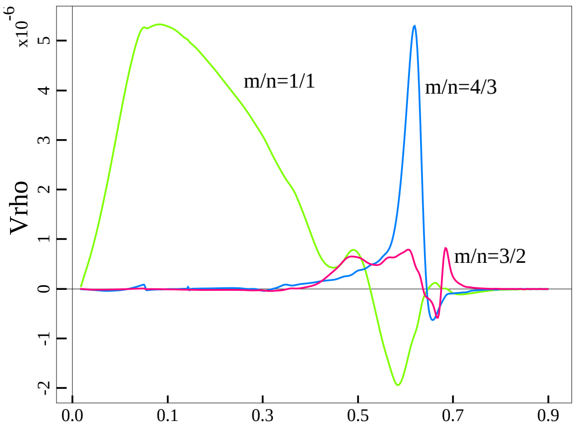

Fig.3

Contour plot of pressure perturbation

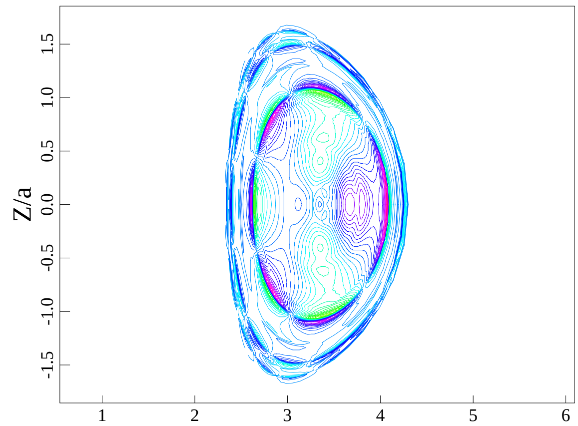

Fig.4

Effect of jcd deposition on island evolution

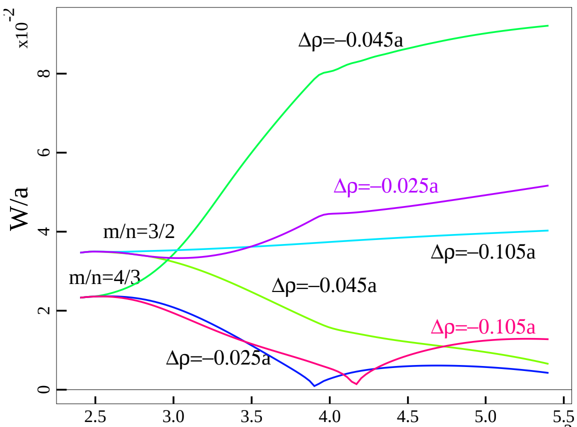

Fig.5

Effect of jcd deposion on 3/2 and 4/3 mode

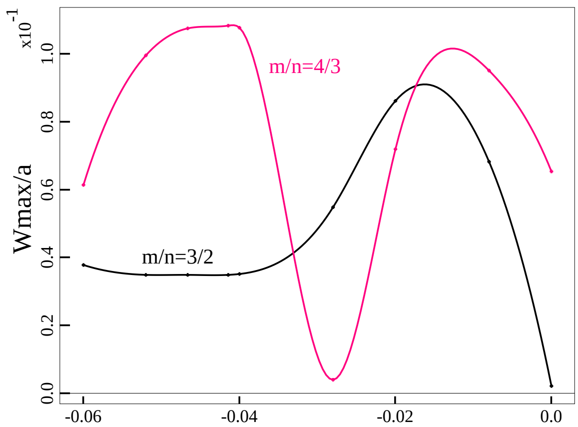

Fig.6