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Excitation of Neoclassical Tearing Modes During Pellet Injection in the Presence of Error Field in ITER

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1. Introduction

Pellet injection into tokamak plasma leads to plasma-pellet interaction which could result in excitation of plasma instability. Experiments on T-10 clearly shows the appearance of ablation bursts when pellet crosses resonance surfaces in plasma [1]. The goal of the report is to show that observed MHD events are connected with excitation of neoclassical tearing modes (NTMs) during pellet penetration. The problem could be important for ITER and calculations were done for real geometry and ITER parameters using the nonlinear three-dimensional magnetohydrodynamic (MHD) code NFTC [2]. Mechanism of NTM excitation and its threshold nature determined by the pellet size is analyzed. The effect of different configurations of external helical magnetic fields on triggering instability is presented.

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 axi-symmetric 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:

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

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

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

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, helical pellet induced current and the Ohmic current density - $j_{\rm BS}$, j_{pel}, j_Ω. The total parallel current density is the sum of Ohmic current and the non-inductive current: $j = j_\Omega + j_{\rm BS} + j_{\rm pel}$. Then $E = \eta j_\Omega = \eta j - E_s$, where the source term is included as $E_s = \eta(j_{\rm BS} + j_{\rm pel})$ The bootstrap current $j_{\rm BS}$ is included in the simplest model form: $j_{\rm BS} = 1.46\sqrt{\varepsilon}[-\frac{\partial P/\partial\rho}{B_{\rm pol}}]$. Current density j_{pel} induced by pellet is represented as a radially localized toroidal current $j_{\rm pel}(\tilde\psi^\star) = I_{\rm pel}\frac{1}{2\pi^{3/2}W_{\rm pel}}e^{\tilde\psi^\star/W^2_{\rm pel}}$ as a function of perturbed normalized helical magnetic flux $\tilde\psi^\star = -(\rho-\rho_s)^2 + \frac{W^2_{mn}}{8}cos(m\theta - n\varphi + \alpha\pi)$. Resistivity η is presented as a sum of equilibrium profile and the localized moving perturbation due to pellet penetration.

$\mathbf{B_{ex}}(\rho,\theta,\varphi)$ is the external helical magnetic field which satisfies the equations inside plasma volume: $[\nabla \times \mathbf{B_{ex}}] = \mathbf{0}$

$(\nabla \cdot \mathbf{B_{ex}}) = \mathbf{0}$ and the boundary conditions on the surface Σ for normal component of magnetic field: $\mathbf{B}_\perp|_\Sigma = \sum_{mn} B^c_{mn}cos(m\theta - n\phi) + B^s_{mn}sin(m\theta - n\phi)$ Coefficients B^c_{mn}, B^s_{mn} permit us to consider different external helical fields configurations. Plasma evolution with high m=1 (in boundary conditions) field configuration hereinafter is called as Hm1 regime and with high m=2 (low m=1) hereinafter is called as Lm1 (low m=1) regime.

3. Effects of pellet-plasma interaction on NTMs excitation.

Inductive scenario 2 for ITER was under the study where the basic equilibrium corresponds to $\beta_N = 1.8$. The following calculations were done for the case when seed islands are created by external helical fields with $B^{m=1}_{ex} = 7.47\cdot 10^{-4}$ and with no j_{pel}. The effect of pellet penetration is modeled by propagation of the narrow cooling front across the plasma volume. Resistivity profile has a step-wise local perturbation with the maximum of perturbation in 1000 times larger then the background resistivity. Fig.1 shows the islands width evolution of different modes during pellet motion. Simulations show the excitation mode by mode. After resistivity perturbation passes resonant surface and mode is excited, there are residual islands exist with no noticeable damping. Growthrates of NTM governed by local resistivity perturbation are much larger in comparison with conventional NTM.

Pellet size and the width of the cooling front determine the threshold effect of NTM excitation. Fig.2 shows the growth rate of the 3/2 island width versus the width of the cooling front. The strong effect of pellet size on 3/2 NTM excitation is seen. When the width of cooling front exceeds $W_{res}/a = 0.012$, then nonlinear growth of island size is observed. Saturation level of growthrate of island is 20 times exceed the conventional NTM level. The dependence of ablation bursts on pellet size was observed in the experiments on T-10 [1].

The reason of NTM excitation is the sharp time increasing of Δ' up to the positive values. The increasing of Δ' determined by large perturbation of current density near rational surface. Fig.3

shows axi-symmetric (m=0) toroidal current perturbation due to external local resistivity (red curve). Green curve is due to the island. It is seen that large perturbation of current density exists near the front site of resistivity perturbation. Also initial bootstrap is large due to the large local pellet pressure gradients. Helical bootstrap current perturbation is damping very fast because of large local resistivity. Different helical modes bursts induced by moving pellet are shown on the conventional NTM diagram ($\frac{dW}{dt}, W$) in fig.4.

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. In the Lm1 regime it is seen that the 3/2 island stabilizes by the 2/1 field harmonic. 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 error fields of the $\mathbf{bex} = \frac{\mathbf{B}^{\rho}_{\mathbf{2/1}}}{B_{\phi 0}} = 0.3 \cdot 10^{-4}$ order in "ITER" 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.5 shows the comparison of the time evolution of magnetic islands in Hm1 and Lm1 regimes. The interaction of the basic modes 3/2,1/1,4/3,2/1 is important and leads to instability of the 4/3 and 3/2 mode. Growthrates of the forced reconnection are much faster in the Hm1 regime. Large pressure perturbation in Hm1 regime is presented in fig.6.

4. Conclusions.

Simulation of NTMs excitation induced by pellet injection in ITER was performed on the base of 3D nonlinear code NFTC. Calculations show that the main reason for tearing mode excitation is the sharp increasing of Δ' on resonant surface of the mode. Destabilizing effect of bootstrap current due to the large perturbation of pressure across the island is also important for ITER. Threshold effect of pellet size on NTM excitation is also obtained in simulations.

The presence of seed islands due to external helical magnetic fields of different configurations in plasma is important for NTMs excitation during pellet penetration.

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] B.Kuteev, et al., JETP Letters,2006,Vol.84,No.5, pp.239-242

[2] A.M.Popov. J.Plasma Physics, Vol.72,2006, P.1101-1104

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Islands excitation Wnm(t) during pellet motion.

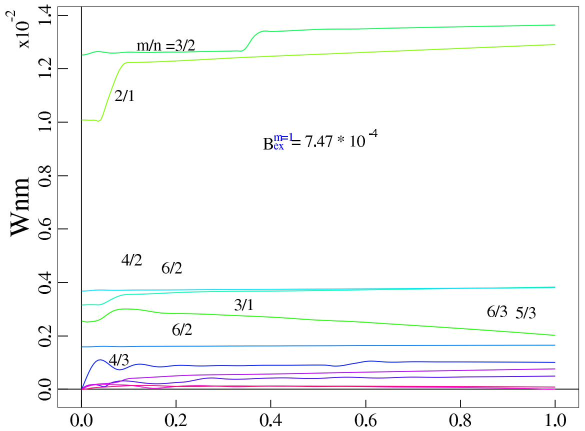

Fig.1

Threshold excitation effect of pellet size

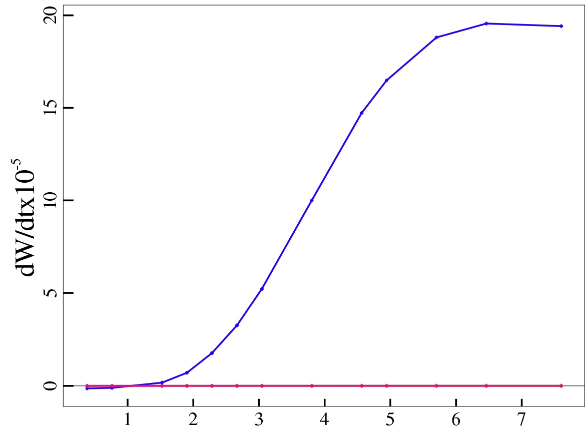

Fig.2

Toroidal current density perturbation n=0,m=0

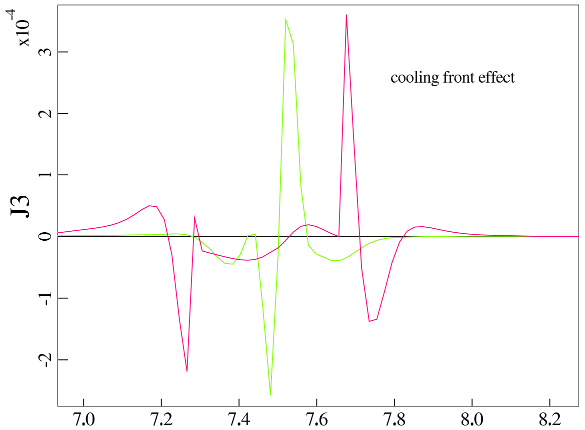

Fig.3

(dW,W). Modes burst induced by moving pellet

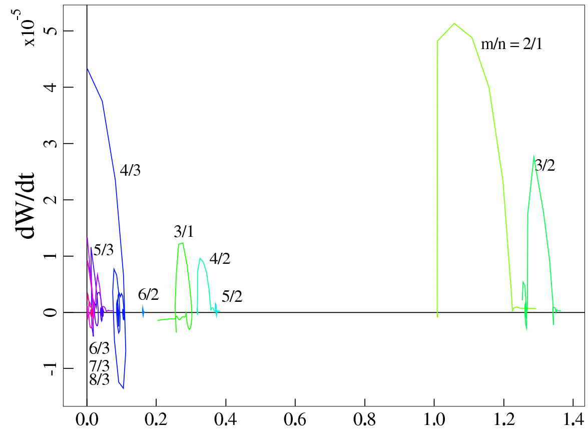

Fig.4

Islands evolution in Hm1 and Lm1 regimes

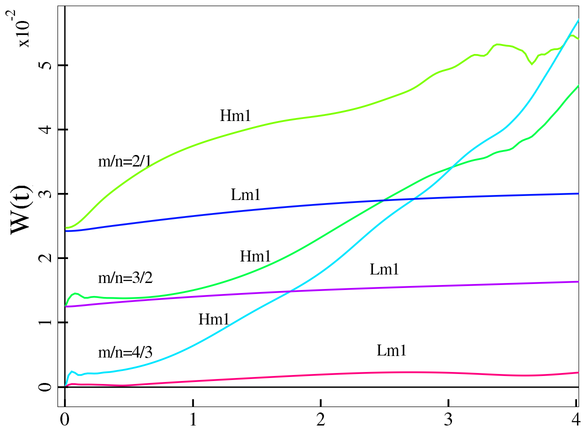

Fig.5

Pressure perturbation in Hm1 regime

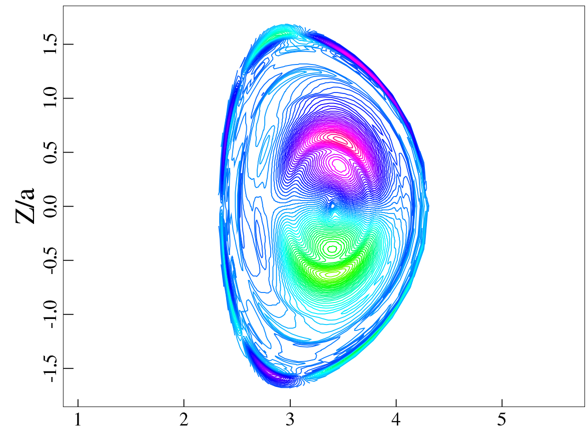

Fig.6